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Engineering Design of Sub-Micron Topographies for Simultaneously Adherent and Reflective Metal-Polymer Interfaces

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(NASA-CR-194573) ENGINEERING DESIGN OF SUB-MICRON TOPOGRAPHIES FOR SIMULTANEOUSLY ADHERENT AND REFLECTIVE METAL-POLYMER INTERFACES (Worcester Polytechnic Inst.) 56 p

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INTRODUCTION

The approach of the project is to base the design of multi-function, reflective topographies on the theory that topographically dependent phenomena react with surfaces and interfaces at certain scales. The first phase of the project emphasizes the development of methods for understanding the sizes of topographic features which influence reflectivity. Subsequent phases, if necessary, will address the scales of interaction for adhesion and manufacturing processes.

A simulation of the interaction of electromagnetic radiation, or light, with a reflective surface is performed using specialized software. Reflectivity of the surface as a function of scale is evaluated and the results from the simulation are compared with reflectivity measurements made on multi-function, reflective surfaces.

METHODS

Simulation

In this work a numerical simulation of light interaction with a surface is compared with reflectivity measurements made at NASA with a Perkin-Elmer Lambda5 scatterometer. Light is emitted from a source, reflected by a surface and then intersects a detector.

Topography

In the simulation, we represented the topography with a 200 x 200 grid of points acquired by a scanning tunneling microscope (STM), where the points are located in a grid in x and y with a height z. The STM work was performed at NASA Langley on a Digital Equipment Nanoscope II. Six topographies were scanned at three scan sizes, 20μm x 20μm, 2μm x 2μm, and 200nm x 200nm (see Table 1).

The large, topographic data sets, used to represent the surface, are analyzed by the patchwork method where the surface, represented by the data points, is tiled with triangular patches (Brown et al. 1992). The topography is evaluated over a range of scales, or patch sizes, by tiling over the surface with decreasing patch sizes. In the simulation each patch represents a reflective facet, atomically smooth and a perfect reflector.

The triangular patches are placed on the surface in two directions: parallel and perpendicular to the STM scan direction. Reflectivity calculations are made for each direction and the results of the simulation are the average of the two calculations.

Lambda5 Scatterometer

We created a computer model of the Perkin-Elmer Lambda5 scatterometer from optical path representations of the scatterometer and reflectivity assembly which were provided by Perkin-Elmer. The incident angle of the light is user-defined, and the detector was modeled as a rectangle at the position and orientation defined by the optical schematic. The size of detector was defined from an engineering drawing of the detector which was provided by Hammamatsu (part number R298 HA). The output of the detector was assigned a value of unity for any intersection of a reflected ray with the detector.

Table 1 STM Scan and Reflectivity Measurements

SURFACE	STM FILENAME	MATERIAL	POINT SPACING X x Y x Z (nm)	REFLECT % 20 DEGREES 531 nm
A	NASA22	T7M1R-P1	100	69.1
A	NASA23	T7M1R-P1	10	69.1
A	NASA24	T7M1R-P1	1	69.1
B	NASA25	P4H1R	100	46.7
B	NASA26	P4H1R	10	46.7
B	NASA27	P4H1R	1	46.7
C	NASA16	D25M2R-P30	100	44.7
C	NASA17	D25M2R-P30	10	44.7
C	NASA18	D25M2R-P30	1	44.7
D	NASA19	T7H3R	100	44.1
D	NASA20	T7H3R	10	44.1
D	NASA21	T7H3R	1	44.1
E	NASA13	D25H1R-P30	100	15.2
E	NASA14	D25H1R-P30	10	15.2
E	NASA15	D25H1R-P30	1	15.2
F	NASA10	P4M1R	100	14.1
F	NASA11	P4M1R	10	14.1
F	NASA12	P4M1R	1	14.1

The light emitted by the source was modeled as set of parallel rays that originate from the source, travel to the surface and are reflected by the center of each patch. One ray is generated for each patch. The direction of the reflected ray is calculated from the incident ray direction and the normal of the patch. From the center of the patch, the ray is reflected off of an optical wedge, a concave, spherical mirror and then it is determined if the ray intersects the detector.

The output of the Lambda5 is percent reflection relative to a known reference sample, in this case the reference sample was a stainless steel mirror provided by Perkin-Elmer. The reflectivity measurements are expressed in terms of a percentage of the measured reflectance from the reference sample.

Reflectivity Simulation

We ran the computerized simulation on the 18 STM data sets with an incident angle of 20 degrees. The simulation generated the incident rays, reflected them off the patches and counted the rays which rays intersected the detector. The output of the simulation R, or absolute percent reflectivity, is defined as the number of incident rays that intersect the detector is divided by the total number of rays reflected by the surface. R is calculated for each patch size and is plotted versus log(patch area). R_R, or relative reflectivity, is calculated from R as

$$R_{RA\text{-}B} = (RA-RB)/RA \qquad \text{[eq. 1]}$$

where RA>RB.

The simulation was modified to account for the effect of patch orientation on the intensity of the incident rays. The intensity of the incident ray, initially equal to one, is multiplied by the cosine of the angle between the patch normal and the incident ray. The ray is then reflected by the patch and the simulation records the number of rays and their intensities that intersect the detctor. The output of the weighted reflectivity simulation, R_w, is

$$R_w = (\Sigma \text{ intensity collected rays}) / \text{number of reflected rays.} \qquad \text{[eq. 2]}$$

Reflectivity Results

We combined the simulation's reflectivity results from the three scans sizes into one larger set of results using Matlab, a matrix-based software program. The large set of results, combined for each of the six surfaces, covered a range of patch areas of 7 orders of magnitude, from 0.5 nm^2 to 3μm^2. Table 2 shows the range of scale for each of the three scan sizes and the data point spacing of the scans.

Table 2. Large and Small Patch Sizes for Three STM Scan Sizes

Scan Size	Large Patch Size	Small Patch Size	Point Spacing
20um x 20um	3 μm^2	5000nm^2	100nm
2 um x 2 um	5000nm^2	50 nm^2	10nm
200 nm x 200nm	50 nm^2	0.5 nm^2	1nm

When the scan sizes were combined, the magnitudes of R did not correspond at the joining patch size. The values of R were shifted by the difference between the scans so as to match at the joining patch size. The R values of the largest scan size (20um x 20um) were used as the zero shift scan when the scans were shifted up, and the R values of the two scans (2μm x 2μm and 200nm x 200nm) were shifted up to the zero shift scan. When the scans were shifted down, the smallest scan size (200nm x 200nm) was the zero shift scan, and the two larger scans were shifted down to it. The shifted results were used to generate plots of absolute reflectivity vs. log(patch area).

Relative reflectivity results were calculated from the shifted scans for shifted up results, and plots of relative reflectivity vs. log(patch area) were generated. Calculation of relative reflectivity (R_R), from eq. 1, was designed to factor out the dependence on the reference sample. Surface A, which has the largest reflectivity measurement, was used as the reference in the plots. A negative value of R_R indicates that the reflectivity of the surface is greater than surface A.

Scale of Interaction

The results of the reflectivity simulation are compared to experimental results, obtained from NASA Langley's Lambda5, to calculate a scale of interaction of the light with the surface. The scale of interaction was defined as the square root of the patch area, from the reflectivity simulation, where the corresponding magnitude of R is equal to the reflectivity value measured by NASA on the Lambda5. Figure 1 shows how a scale of interaction is found from the simulation and experimental results.

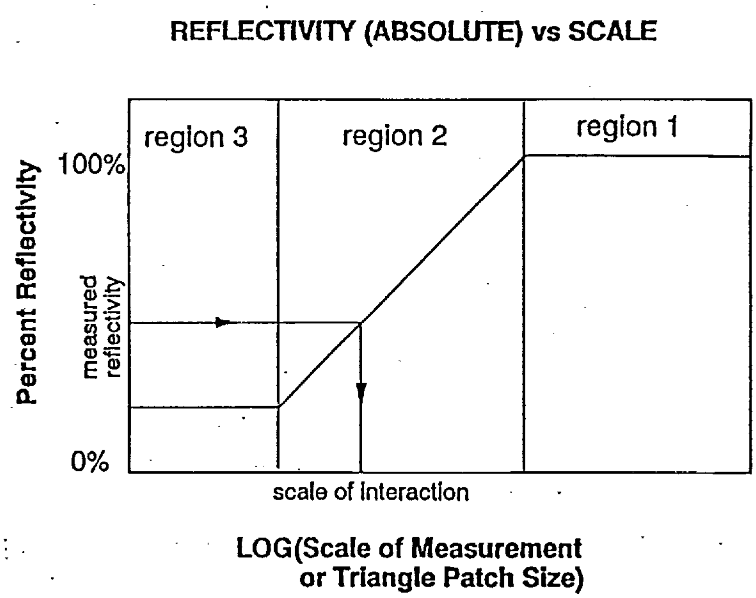


Figure 1- Schematic of Calculation of Scale of Interaction from Idealized, Absolute Reflectivity vs. Scale The intersection of the measured reflectivity is found, and the scale of interaction is calculated from the corresponding patch size. The scale of interaction is shown to occur in region 2.

RESULTS

Relative Area

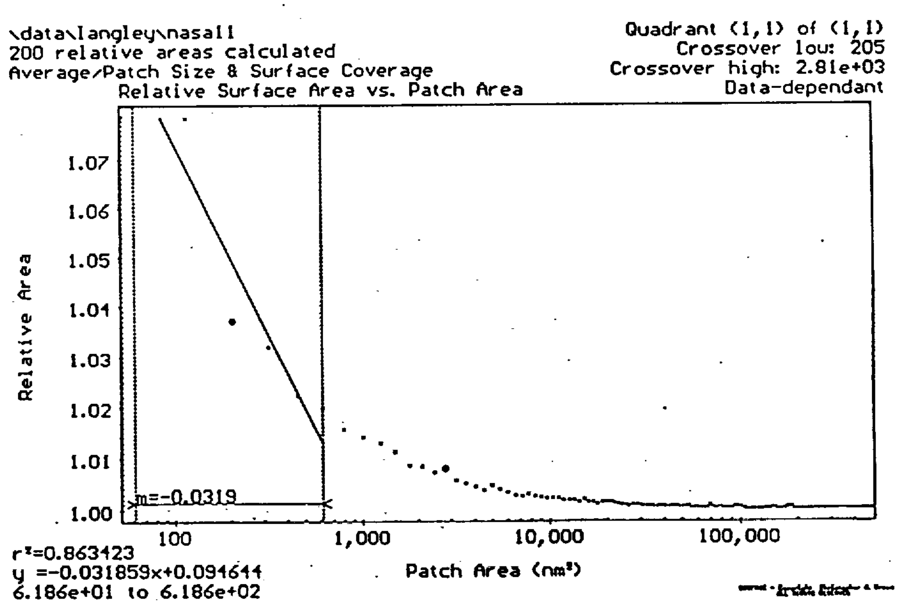
The STM data sets were analyzed by the patchwork method and a representative scale-area plot is shown in figure 2 (Brown et al. 1993). The scale-area analyses were conducted on each of the three scan sizes separately. All of the scale-area plots are found in Appendix A.

Absolute Reflectivity
Absolute reflectivity as a function of scale, or patch area, was calculated by the reflectivity simulation. Shifted up an shifted down results for surface A are shown in Figures 3 and 4. Absolute reflectivity plots for the six surfaces are found in Appendix B.

Cosine Weighting - incident angle
Absolute, cosine-weighted reflectivity as a function of scale, for surface B, is plotted with non-weighted results in Figure 5. Cosine-weighted results for the six surfaces are found in Appendix C.

Relative Reflectivity
Relative reflectivity as a function of scale, for surface B relative to A, is shown in figure 5. Relative reflectivity plots for surfaces B through F, relative to A, were generated using shifted up results. The plots are found in Appendix C.

Scale of Interaction
A scale of interaction was calculated from the absolute reflectivity plots. Table 3 lists the scales of interaction found using the absolute reflectivity results. The reflectivity measurements did not intersect the relative reflectivity results, and no scales of interaction were found.



<u>Figure 2 - Scale-Area Plot of Surface A.</u> The 2mm x 2mm scan size is shown for surface A. The relative area begins to increase (crossover) at a patch area of 2810 nm^2.

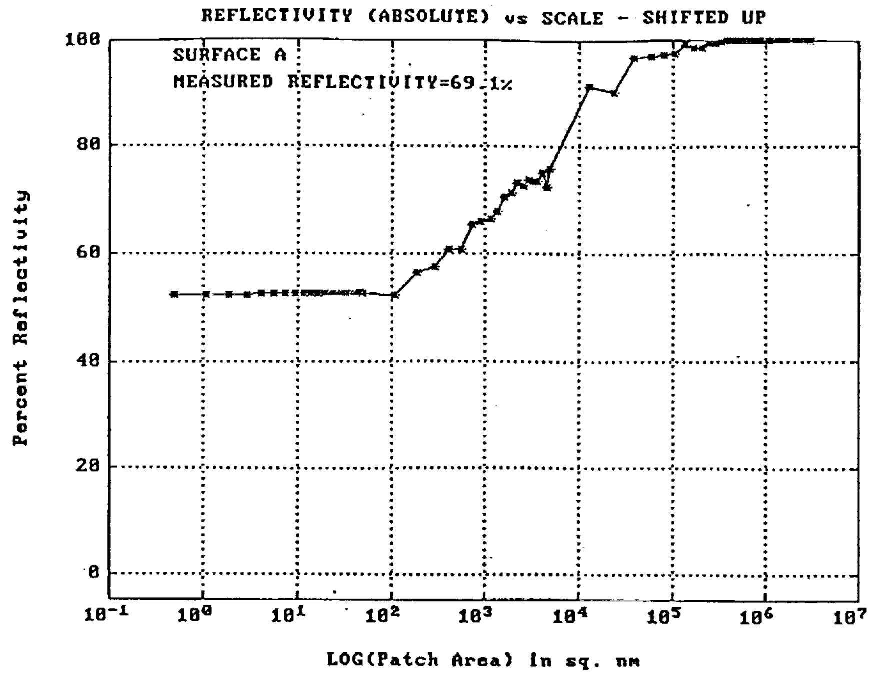


Figure 3 - Shifted Up Absolute Reflectivity Results for Surface A The percent reflectivity is 100% at large patch areas and decreases to about 53% at the fine patch sizes. The largest scan size was used as the no shift scan.

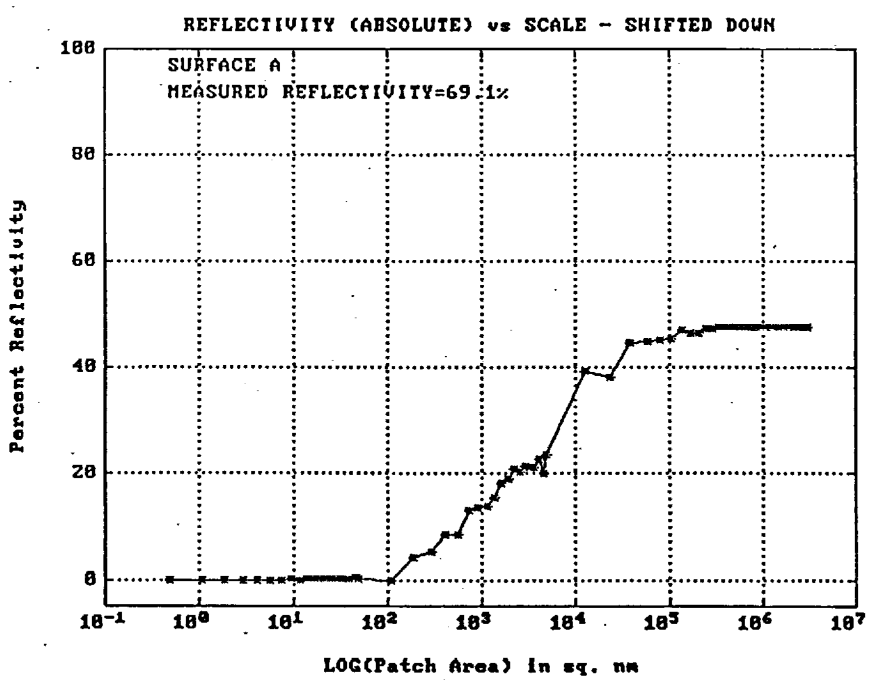


Figure 4 - Shifted Down Absolute Reflectivity Results for Surface A. The percent reflectivity is about 48% at large patch areas and decreases to about 0% at the fine patch sizes. The smallest scan size was used as the no shift scan.

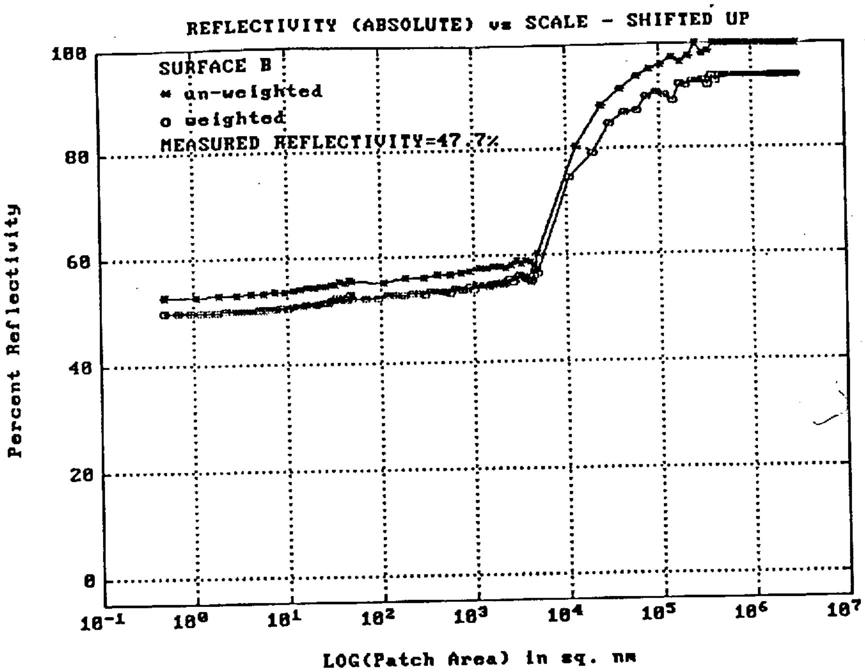


Figure 5 - Incident Angle Cosine-Weighted and Non-Weighted Absolute Reflectivity Results for Surface B. The difference between the cosine weighted and unweighted results is shown. Cosine weighting shifts the set of results down by a factor of 0.94 (a multiplier of cosine 20°), or shifting the results down by 6%. The results are shifted by an equal percentage at all scales.

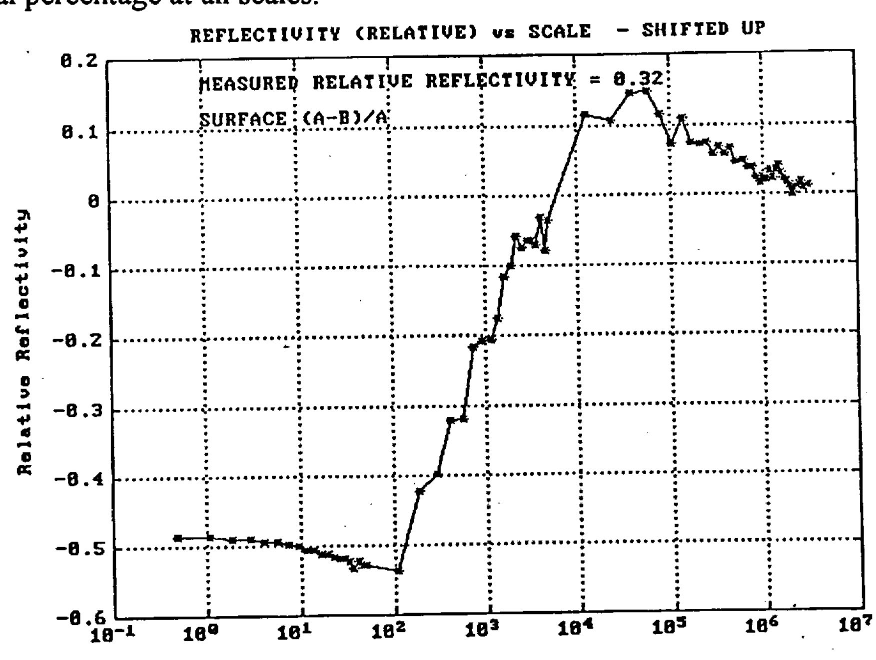


Figure 6 - Relative Reflectivity Results for Surface B Relative to Surface A. The maximum relative reflectivity value is about .15 which is less than the measured result. R_R is negative at patch areas less than about 500 nm^2.

Table 3 Scales of Interaction from Absolute Reflectivity Results. Surface A is the surface with a scale of interaction from the shifted up results. The scales from the shifted down differ by about 1 order of magnitude.

Surface	Scale of Interaction (nm) shifted up	Scale of Interaction (nm) shifted down
A	39	x
B	x	x
C	x	102
D	x	164
E	x	13
F	x	18

DISCUSSION

Relative Area

The scale-area plots show that the reflective topographies are complex at fine scales, and the relative areas, a measure of complexity, increase with decreasing patch size. The difference between the relative areas of the three scan sizes is clear: the maximum, relative areas of the 200nm x 200nm scan size are approximately 2 orders of magnitude larger than that of the 2 μm x 2μm scan size and approximately three orders of magnitude larger the smallest scan size.

Absolute Reflectivity

The plots show three distinct regions over a range of scale. In region 1, occurring at patch sizes down to 10^5 nm^2, the percentage reflectivity (R) remains constant over a range of patch sizes. Decreasing patch size does not change the amount of reflected light that reaches the detector, and R is largest in this region.

In region 2, occurring at patch sizes from 10^5 nm^2 to 100 nm^2, R decreases with decreasing patch size. Decreasing patch size decreases the amount of reflected light that reaches the detector, and R in this region is less than region 1 and greater than region 3.

In region 3, occurring from a patch size of 100 nm^2 to 0.5 nm^2, R remains constant. Decreasing patch size no longer decreases the amount of light that reaches the detector, and R is lowest in this region.

The material properties of the surfaces, i.e., conductivity, absorbtivity and transmissivity, were not considered in the simulation, and would shift the plots down from the shifted up condition. The downward shift would increase the calculated scale of interaction, and, depending on the size of the shift, would cause the measured reflectivity results to intersect the simulation's results.

Incident angle cosine weighting shifts the reflectivity simulation results down for all of the surfaces, and the percentage shift is constant for all scales. It is speculated that the percentage shift is constant at all scales because the collector is small, and only rays close to the direction of specular reflection are collected. Reflected rays with a weighting factor close to zero would reduce the results by more than 6%, but these rays, with a small weighting factor, will not be reflected close to the specular direction, and will not intersect the detector. The weighting factors of the collected rays are close to cosine (20°), and shift the results down by 6%.

Relative Reflectivity

The measured results do not intersect the relative reflectivity results at any scale, which may be because the scale of interaction theory is wrong or because we are misinterpreting the results of the reflectivity measurements. It was expected that all relative values would be positive, at least at one scale, because the calculations were made relative to the surface with the largest reflectivity measurement, surface A, and that this scale would correlate with the reflectivity measurements. The plots show that surface A is less reflective than most of the other surfaces and that the surface with the largest R_R changes with scale.

The reflectivity measurements made by NASA are expressed as a percentage reflectivity of a stainless steel reference sample. It is not yet clear how we should interpret this representation of reflectivity compared to the computer simulation. Relative reflectivity plots were generated to factor out the dependence on the reference sample, but we have not been successful. Including conductivity and absorbtivity of the reference sample in the computer simulation may provide a truer representation of NASA's reflectivity method. Also, more information about how the Lambda5 processes the output signal from the photo multiplier tube may give a better understanding of the equipment's output.

Scale of Interaction

Joining the three scan sizes effects the scale of interaction calculation; shifting up decreases the scale and shifting down increases it. Possible causes of mismatch at joining patch areas are the patch placement algorithm, differences in the STM scan parameters for the three scan sizes or variability in material properties over the different scan areas.

The current algorithm places a small number of patches at the large scales (large with respect to data point spacing), and may provide a poor representation of the topography. Since the topography may be more precisely represented with decreasing patch size, the joining patch size may be thought of as a boundary separating regions of high and low precision.

Changes in material properties of a surface will also change how the tip interacts with the topography. Efforts were made to minimize the effect of local changes in material properties, but the scans may have been effected to some degree.

Future Work

The work will be continued under a NASA training grant, grant number NGT-51107. In future work other reflectivity methods, such as total integrated scattering (TIS), will be investigated as a means for better understanding the amount of energy reflected by the surfaces. Reflectivity samples will made from homogeneous materials to reduce the complexity of the reflectivity simulation by eliminating multiple layer materials and distributed reflective particles. Random patch placement algorithms will be investigated that may better represent the interaction of light with the surfaces.

CONCLUSIONS

1. The scale-area plots show that the reflective topographies are complex at fine scales, and that the relative areas, a measure of complexity, increase with decreasing patch size.

2. Simulation of a reflecting surface as a collection of triangular mirrors and decreasing the size on each repetition results in a steady decrease in the amount of light arriving at a detector, indicating increasing scatter or diffuse reflection at finer scales.

3. Ranking of the surfaces based on reflectivity calculated from the current algorithm does not correspond at any scale, to the ranking from reflectivity measurement, as they are currently interpreted.

4. The scales of interaction calculated from the current algorithm do not share a common region of reflectivity with the measured values.

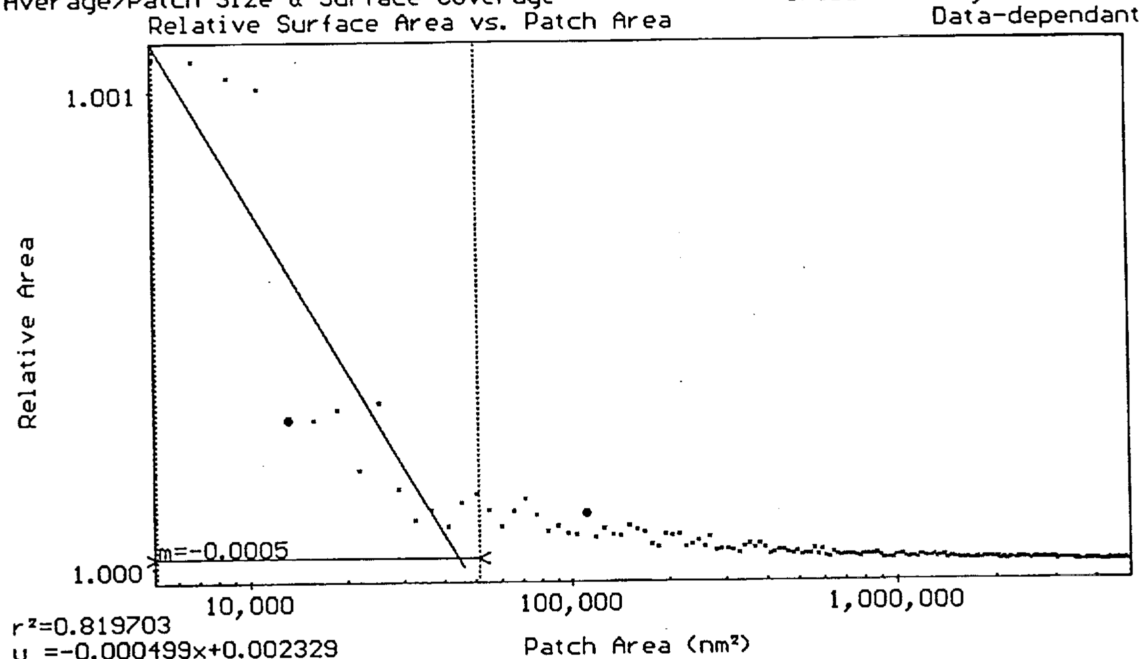
REFERENCES

C.A. Brown, P.D. Charles, W.A. Johnsen, S. Chesters, "Fractal analysis of topographic data by the patchwork method",WEAR, 161, 61-67, (1993).

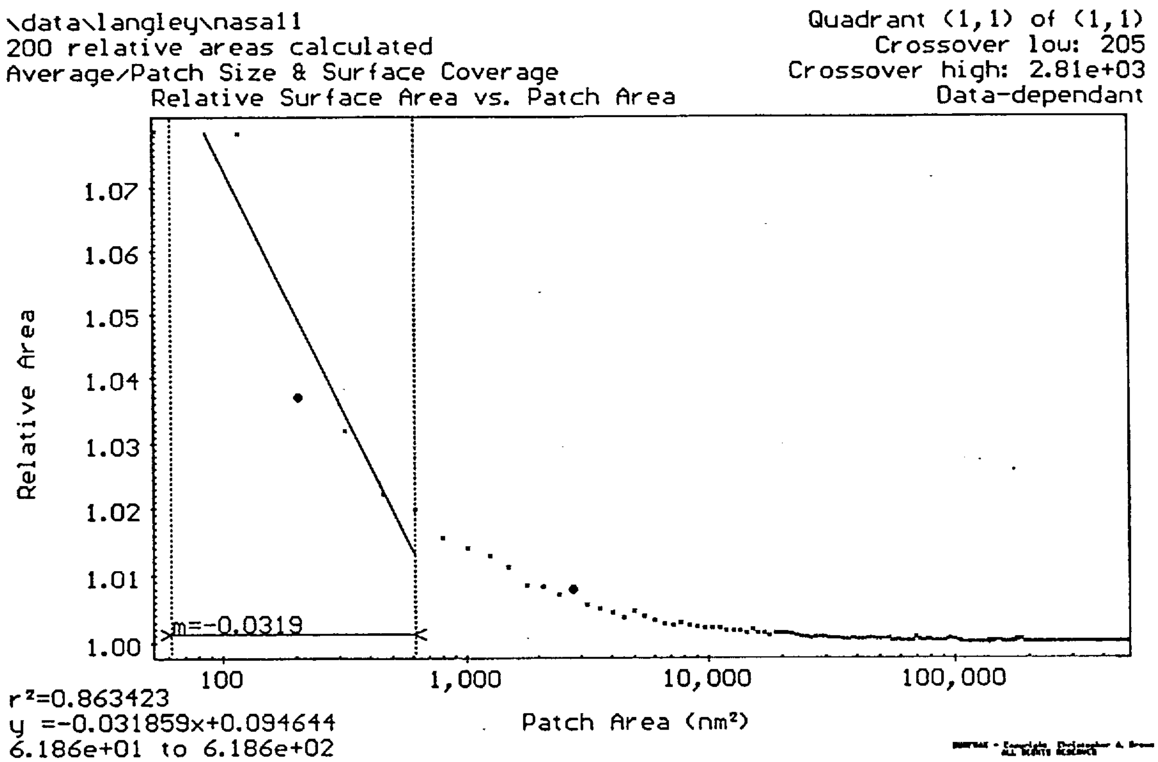
Appendix A
Scale-Area plots

\data\langley\nasa10
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 1.33e+04
Crossover high: 1.11e+05
Data-dependant



r^2=0.819703
y =-0.000499x+0.002329
5.133e+03 to 5.133e+04

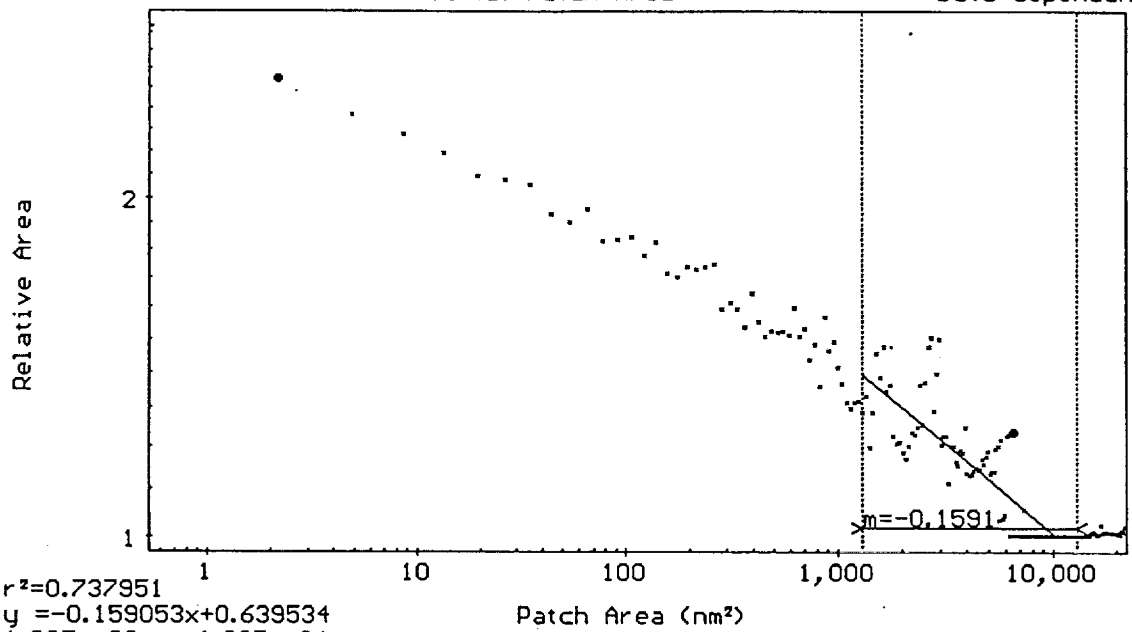


\data\langley\nasa11
200 relative areas calculated
Average/Patch Size & Surface Coverage
Relative Surface Area vs. Patch Area
Quadrant (1,1) of (1,1)
Crossover lou: 205
Crossover high: 2.81e+03
Data-dependant
Relative Area
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
m=-0.0319
100
1,000
10,000
100,000
Patch Area (nm²)
r²=0.863423
y =-0.031859x+0.094644
6.186e+01 to 6.186e+02

\data\langley\nasa12
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 2.16
Crossover high: 6.53e+03
Data-dependant

Relative Surface Area vs. Patch Area

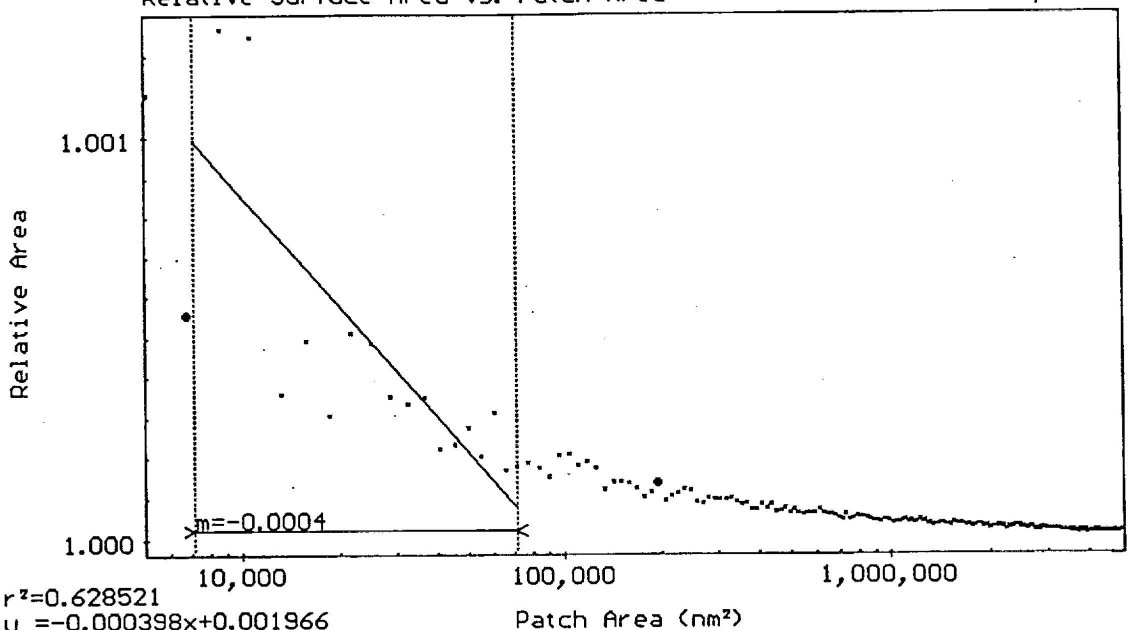


$r^2=0.737951$
$y = -0.159053x+0.639534$
1.297e+03 to 1.297e+04

\data\langley\nasa13
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 6.76e+03
Crossover high: 1.95e+05
Data-dependant

Relative Surface Area vs. Patch Area

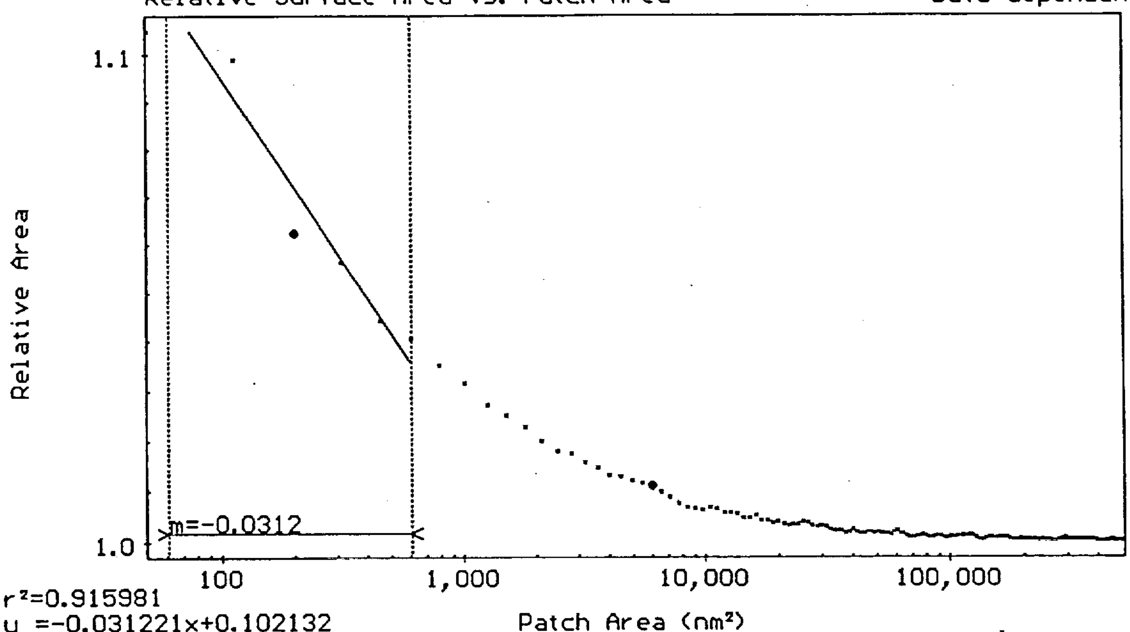


r^2=0.628521
y =-0.000398x+0.001966
7.136e+03 to 7.136e+04

\data\langley\nasa14
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 200
Crossover high: 6e+03
Data-dependant

Relative Surface Area vs. Patch Area

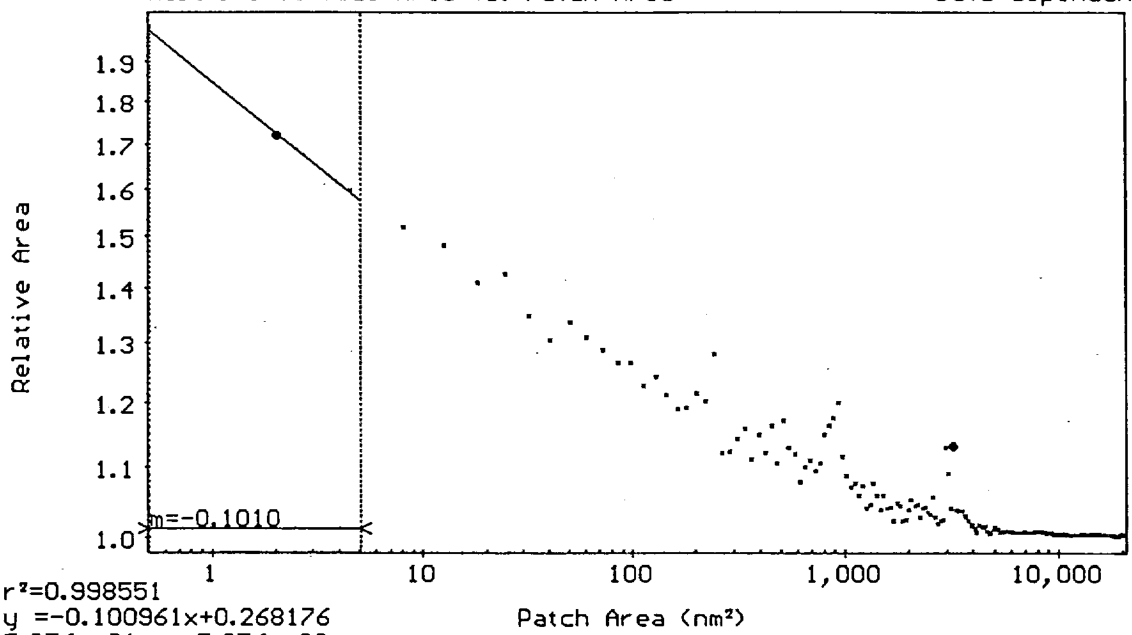


r^2=0.915981
y =-0.031221x+0.102132
6.096e+01 to 6.096e+02

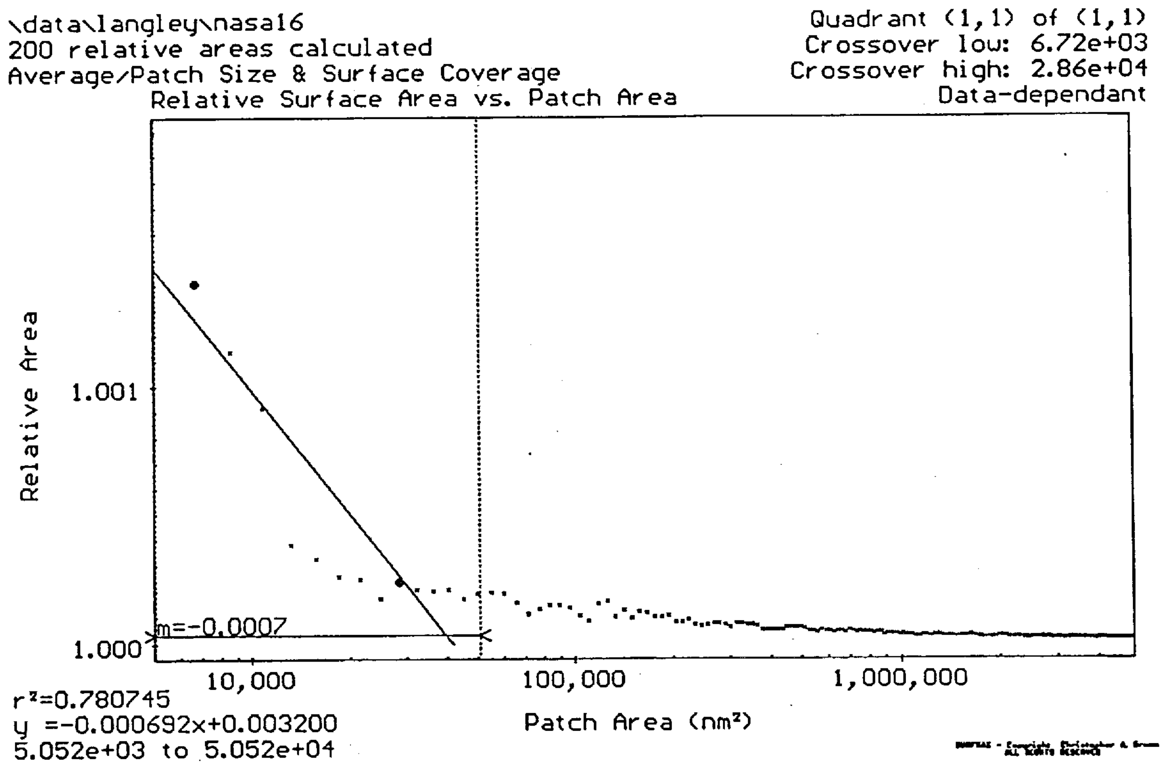
\data\langley\nasa15
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 2.02
Crossover high: 3.22e+03
Data-dependant

Relative Surface Area vs. Patch Area



r^2=0.998551
y =-0.100961x+0.268176
5.076e-01 to 5.076e+00

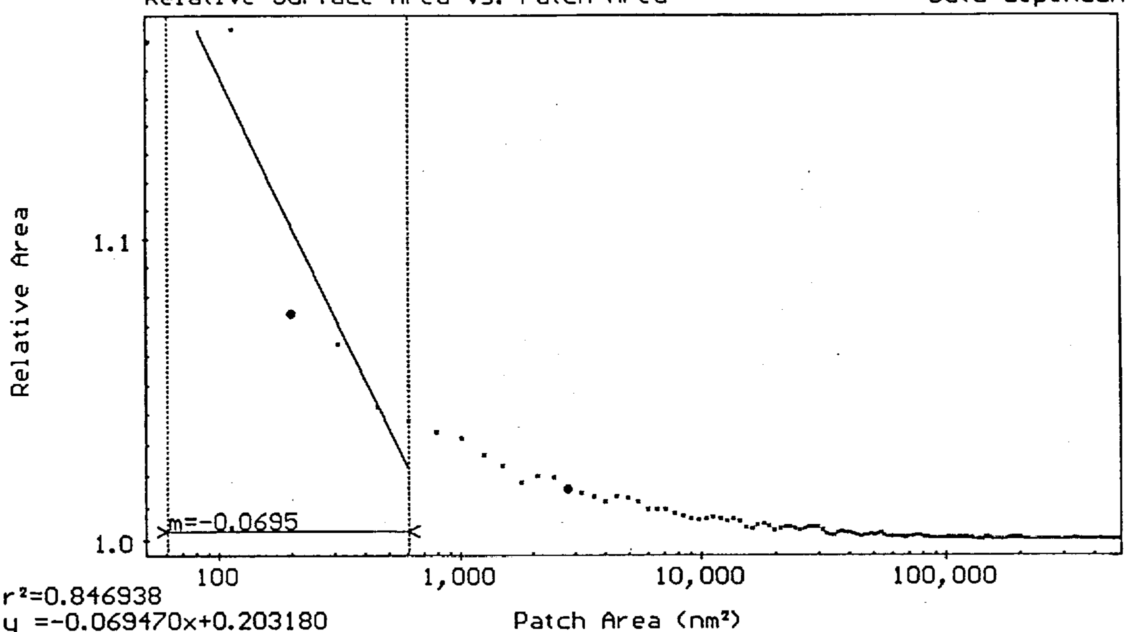


\data\langley\nasa16
200 relative areas calculated
Average/Patch Size & Surface Coverage
Relative Surface Area vs. Patch Area
Quadrant (1,1) of (1,1)
Crossover low: 6.72e+03
Crossover high: 2.86e+04
Data-dependant
Relative Area
1.001
1.000
m=-0.0007
10,000
100,000
1,000,000
Patch Area (nm²)
r²=0.780745
y =-0.000692x+0.003200
5.052e+03 to 5.052e+04

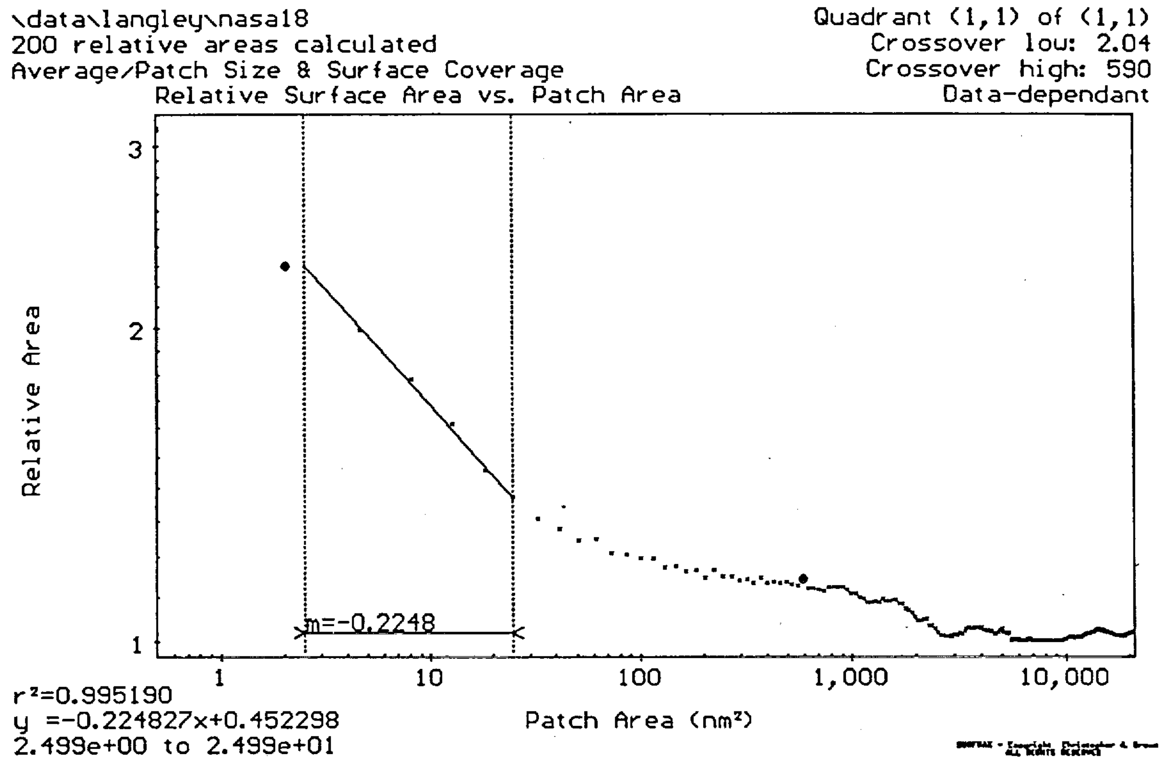
\data\langley\nasa17
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 200
Crossover high: 2.79e+03
Data-dependant

Relative Surface Area vs. Patch Area



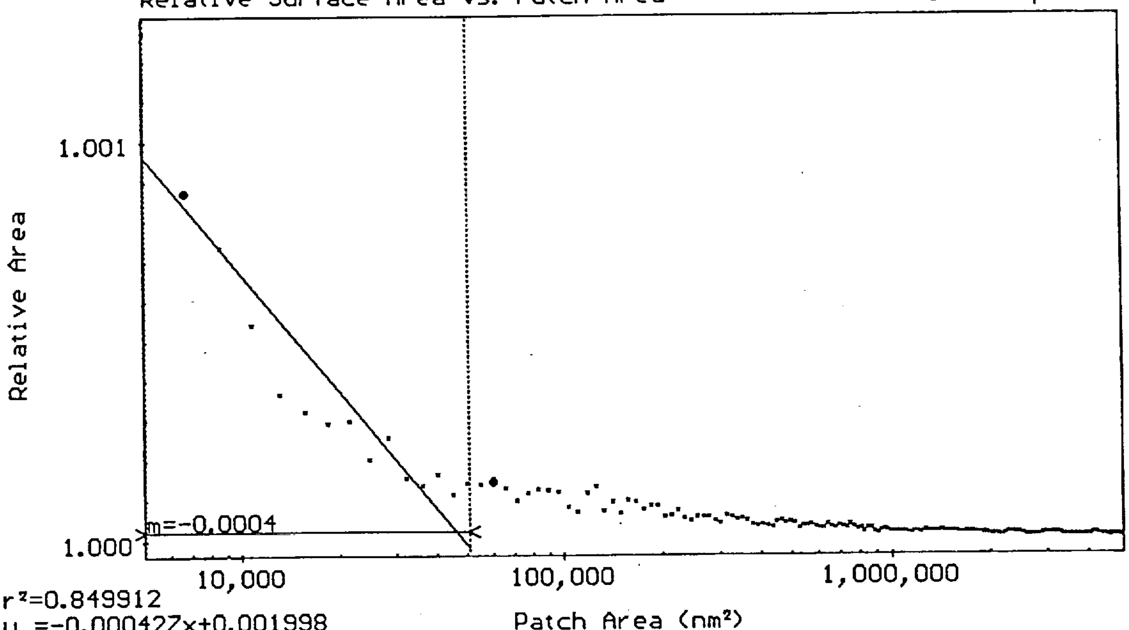
r^2=0.846938
y =-0.069470x+0.203180
6.098e+01 to 6.098e+02


\data\langley\nasa18
200 relative areas calculated
Average/Patch Size & Surface Coverage
Relative Surface Area vs. Patch Area
Quadrant (1,1) of (1,1)
Crossover low: 2.04
Crossover high: 590
Data-dependant
Relative Area
3
2
1
m=-0.2248
1
10
100
1,000
10,000
Patch Area (nm²)
r²=0.995190
y =-0.224827x+0.452298
2.499e+00 to 2.499e+01

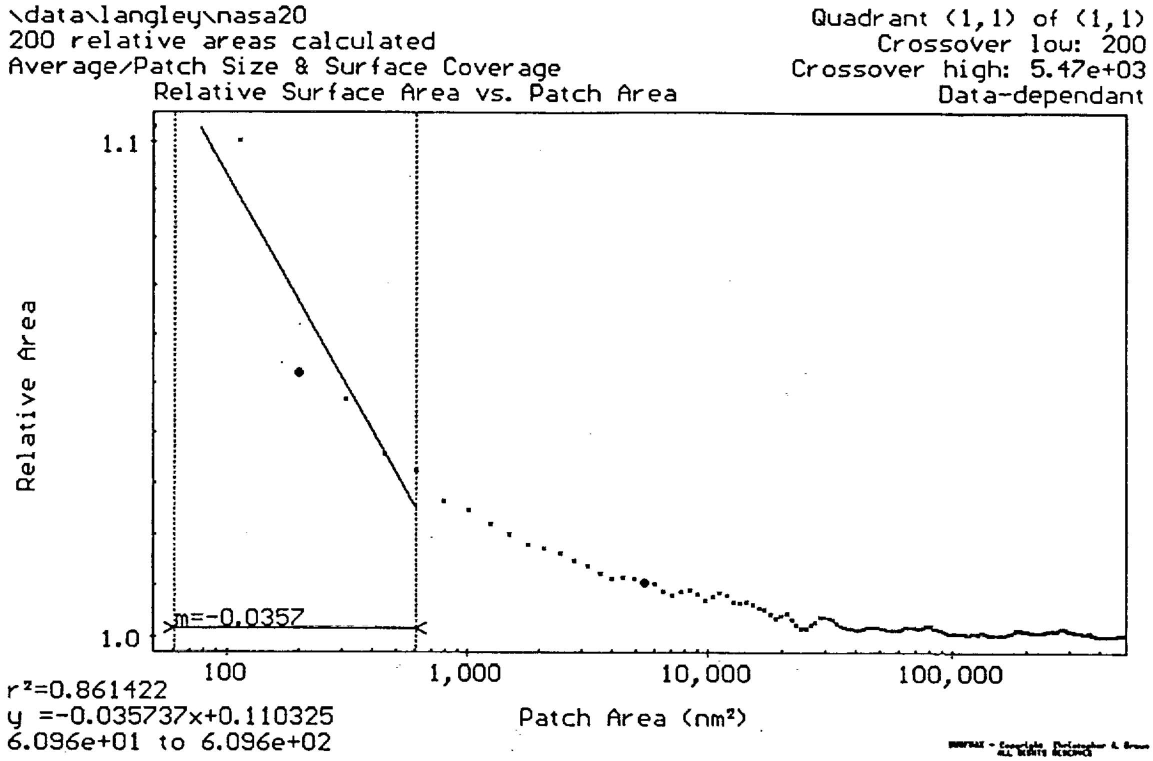
\data\langley\nasa19
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 6.72e+03
Crossover high: 6.01e+04
Data-dependant

Relative Surface Area vs. Patch Area



r^2=0.849912
y =-0.000427x+0.001998
5.052e+03 to 5.052e+04

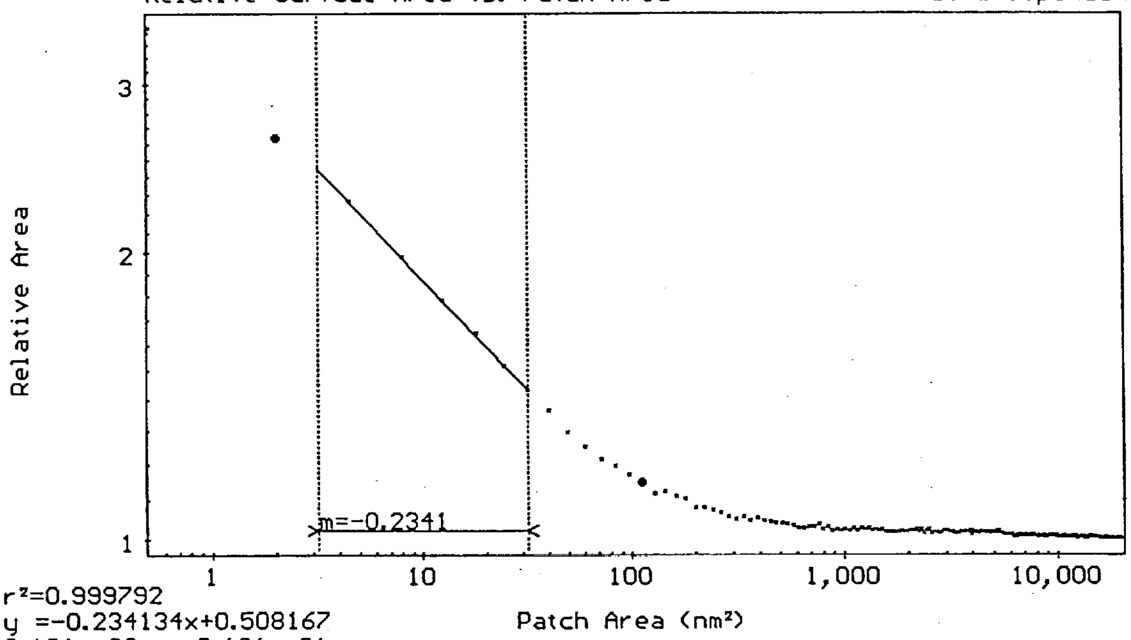


\data\langley\nasa20
200 relative areas calculated
Average/Patch Size & Surface Coverage
Relative Surface Area vs. Patch Area
Quadrant (1,1) of (1,1)
Crossover low: 200
Crossover high: 5.47e+03
Data-dependant
Relative Area
1.1
1.0
m=-0.0357
100
1,000
10,000
100,000
Patch Area (nm²)
r²=0.861422
y =-0.035737x+0.110325
6.096e+01 to 6.096e+02

\data\langley\nasa21
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 2
Crossover high: 112
Data-dependant

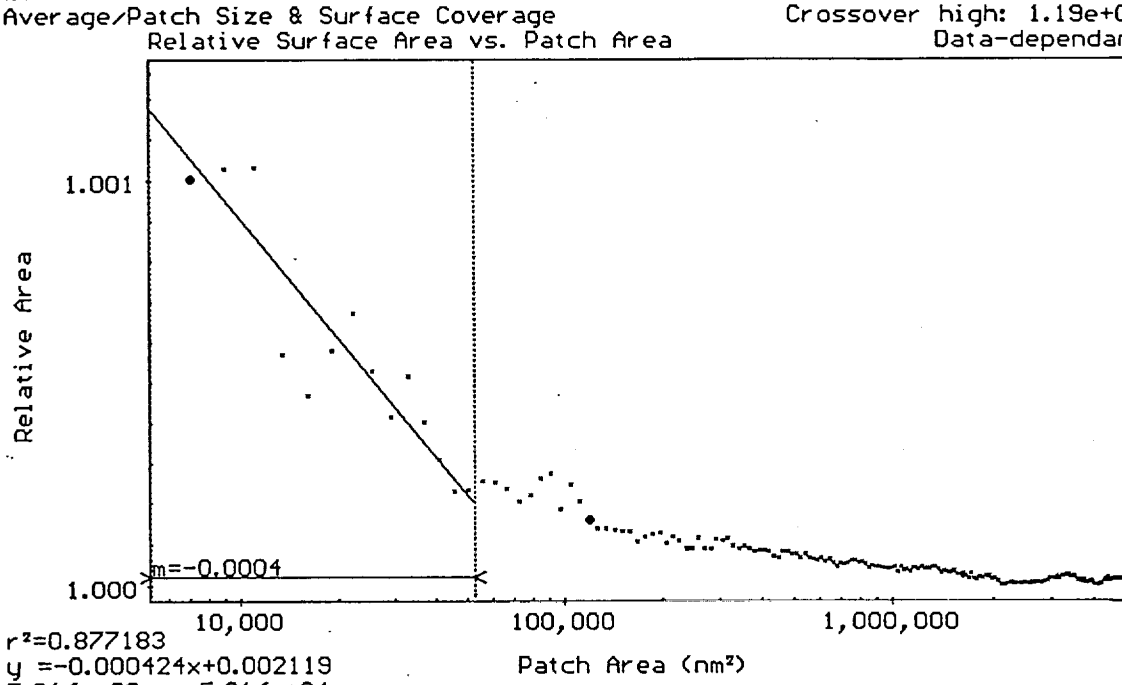
Relative Surface Area vs. Patch Area



r^2=0.999792
y =-0.234134x+0.508167
3.181e+00 to 3.181e+01

\data\langley\nasa22
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 7.02e+03
Crossover high: 1.19e+05
Data-dependant

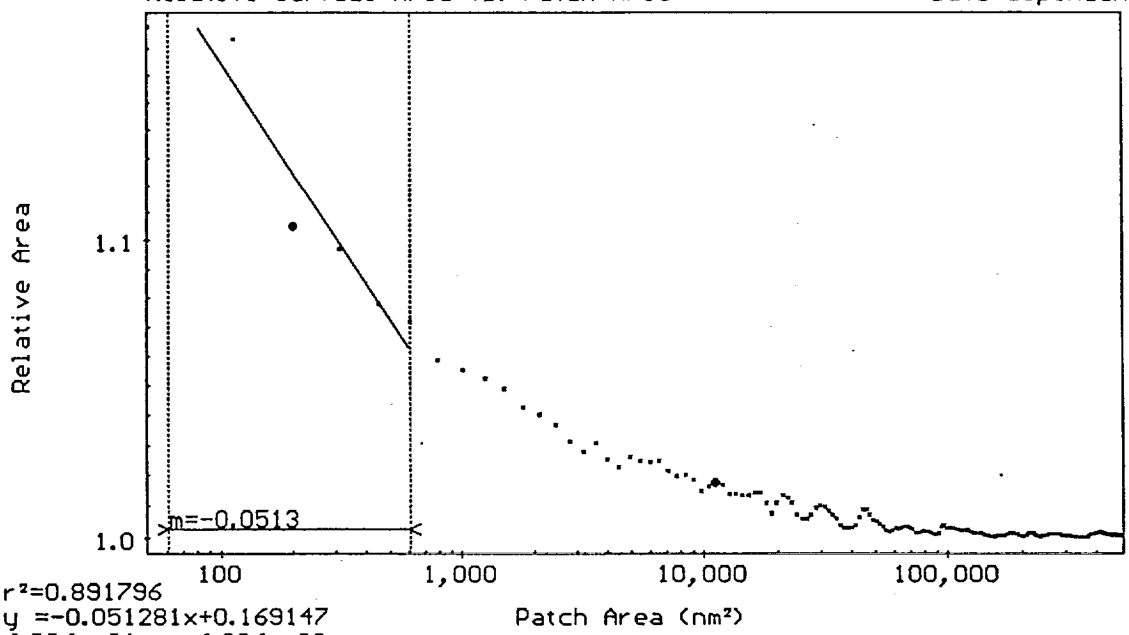


r^2=0.877183
y =-0.000424x+0.002119
5.316e+03 to 5.316e+04

\data\langley\nasa23
200 relative areas calculated
Average/Patch Size & Surface Coverage

Quadrant (1,1) of (1,1)
Crossover low: 200
Crossover high: 1.12e+04
Data-dependant

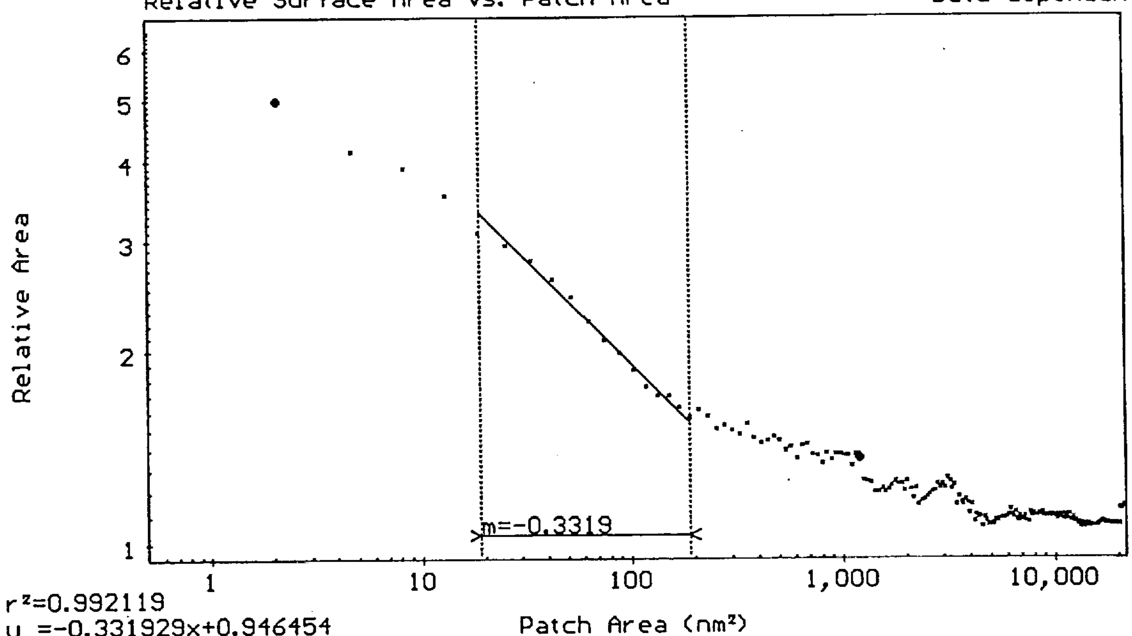
Relative Surface Area vs. Patch Area



r^2=0.891796
y =-0.051281x+0.169147
6.096e+01 to 6.096e+02

\data\langley\nasa24
200 relative areas calculated
Average/Patch Size & Surface Coverage
Relative Surface Area vs. Patch Area

Quadrant (1,1) of (1,1)
Crossover low: 2.06
Crossover high: 1.21e+03
Data-dependant

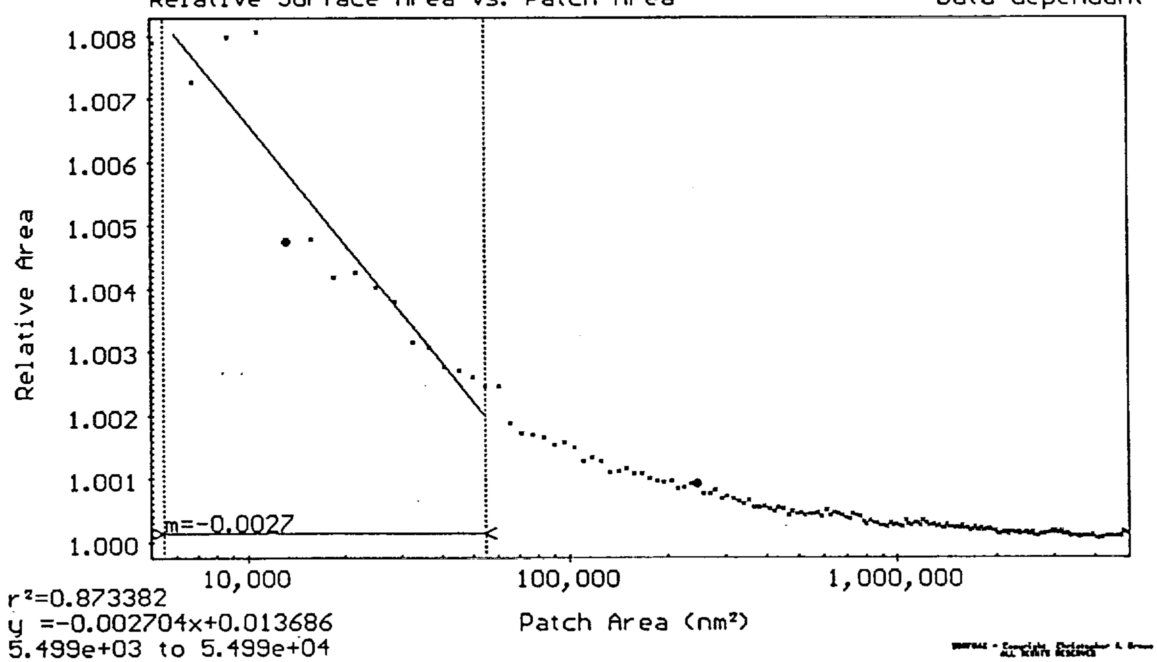


r^2=0.992119
y =-0.331929x+0.946454
1.890e+01 to 1.890e+02

\data\langley\nasa25
200 relative areas calculated
Average/Patch Size & Surface Coverage

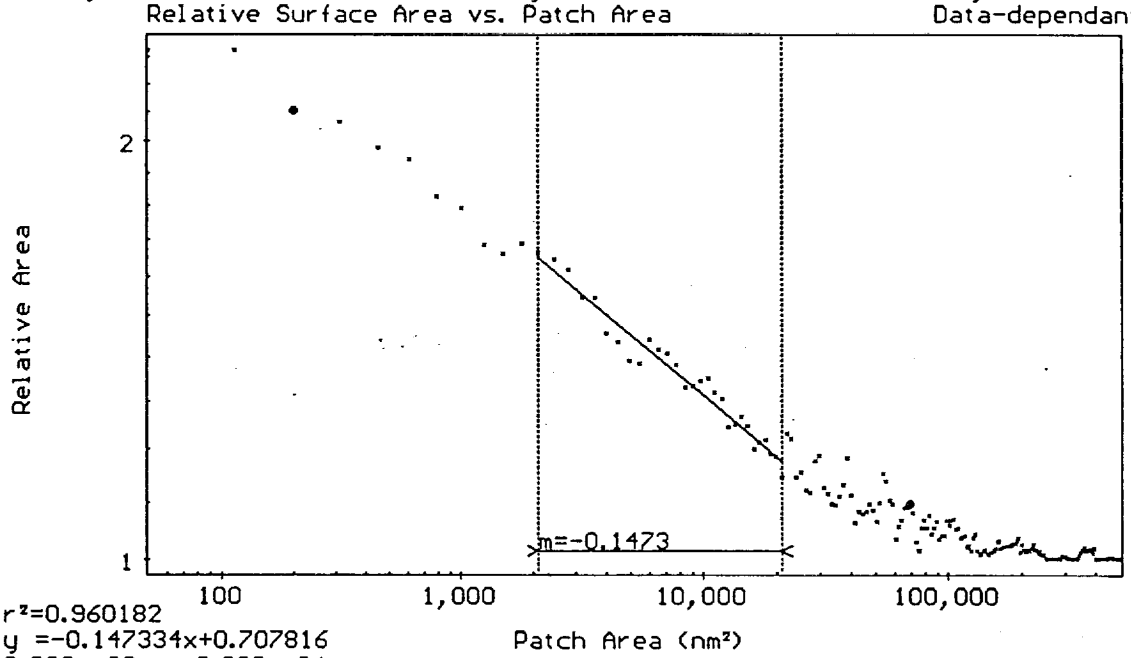
Quadrant (1,1) of (1,1)
Crossover low: 1.32e+04
Crossover high: 2.46e+05
Data-dependant

Relative Surface Area vs. Patch Area



\data\langley\nasa26
200 relative areas calculated
Average/Patch Size & Surface Coverage
Relative Surface Area vs. Patch Area

Quadrant (1,1) of (1,1)
Crossover low: 200
Crossover high: 6.96e+04
Data-dependant

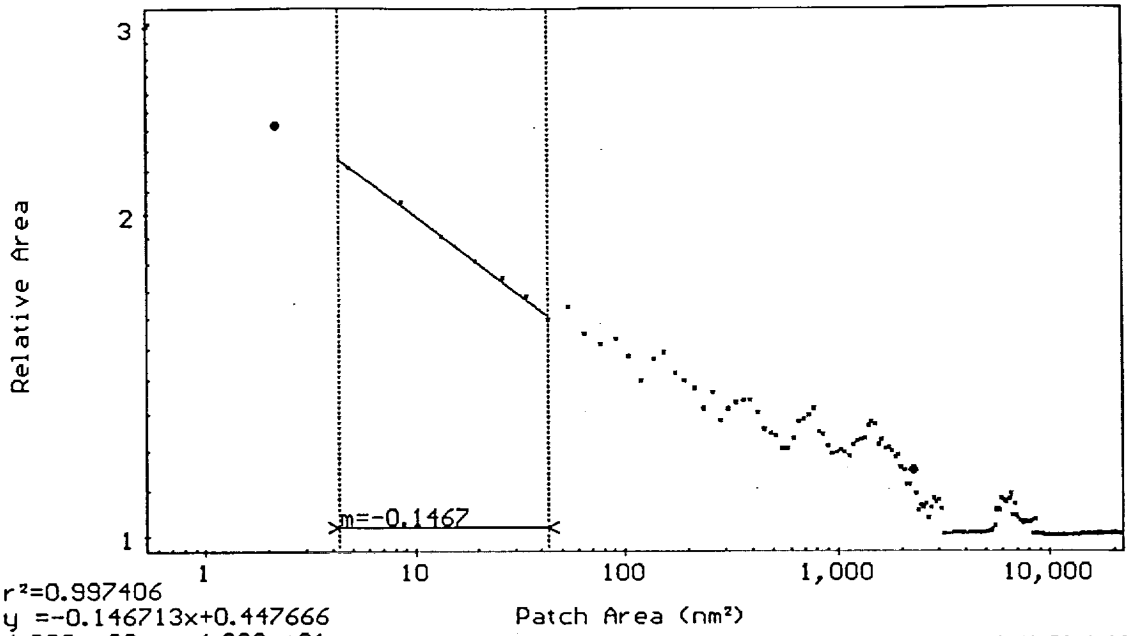


r^2=0.960182
y =-0.147334x+0.707816
2.082e+03 to 2.082e+04

\data\langley\nasa27
200 relative areas calculated
Average/Patch Size & Surface Coverage

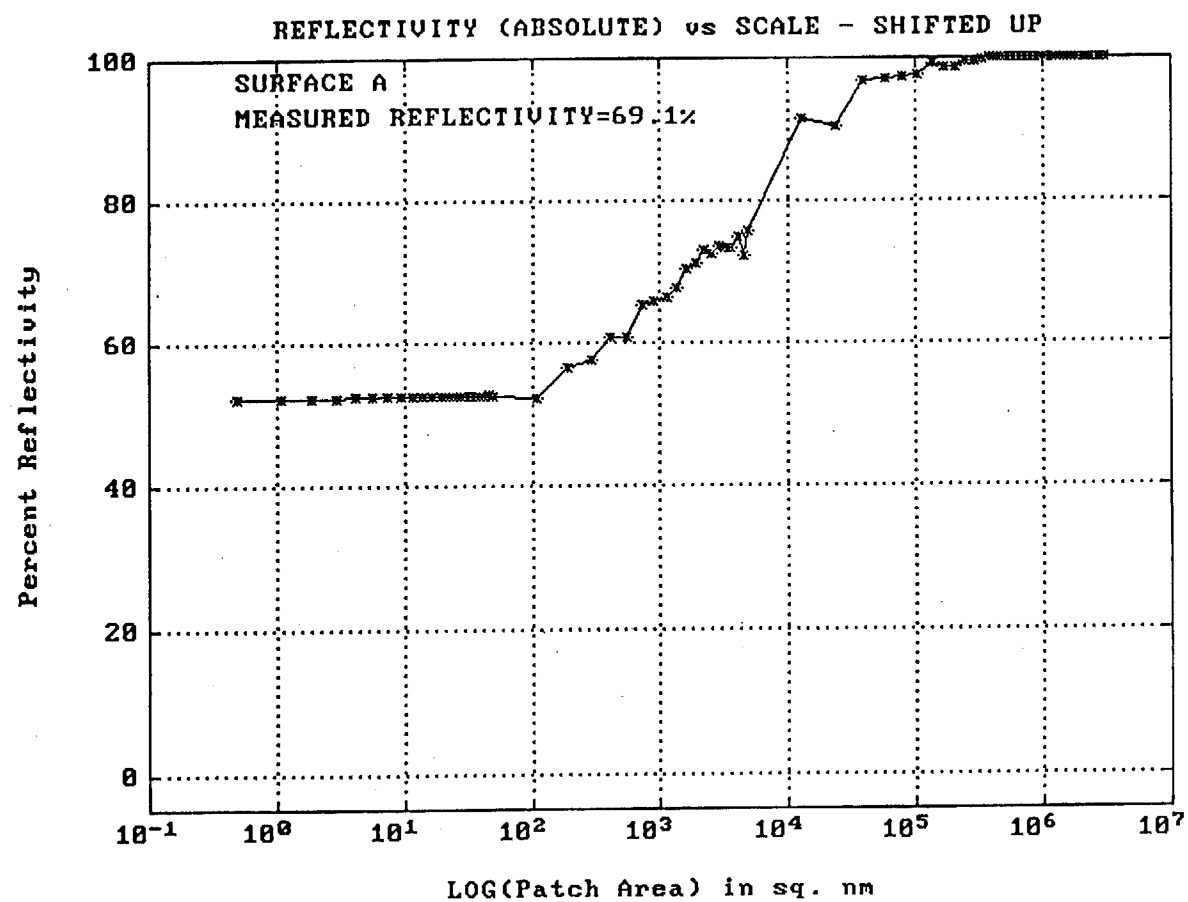
Quadrant (1,1) of (1,1)
Crossover low: 2.15
Crossover high: 2.26e+03
Data-dependant

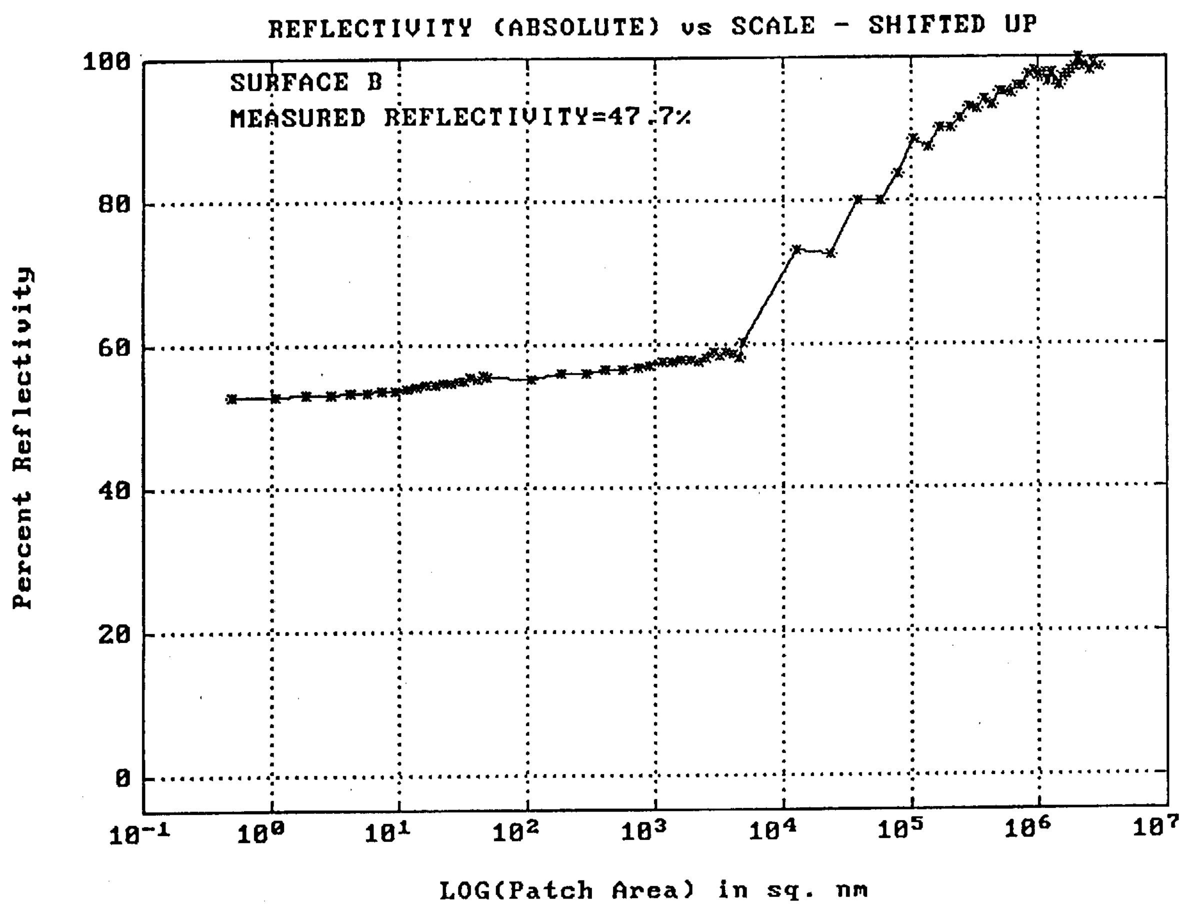
Relative Surface Area vs. Patch Area



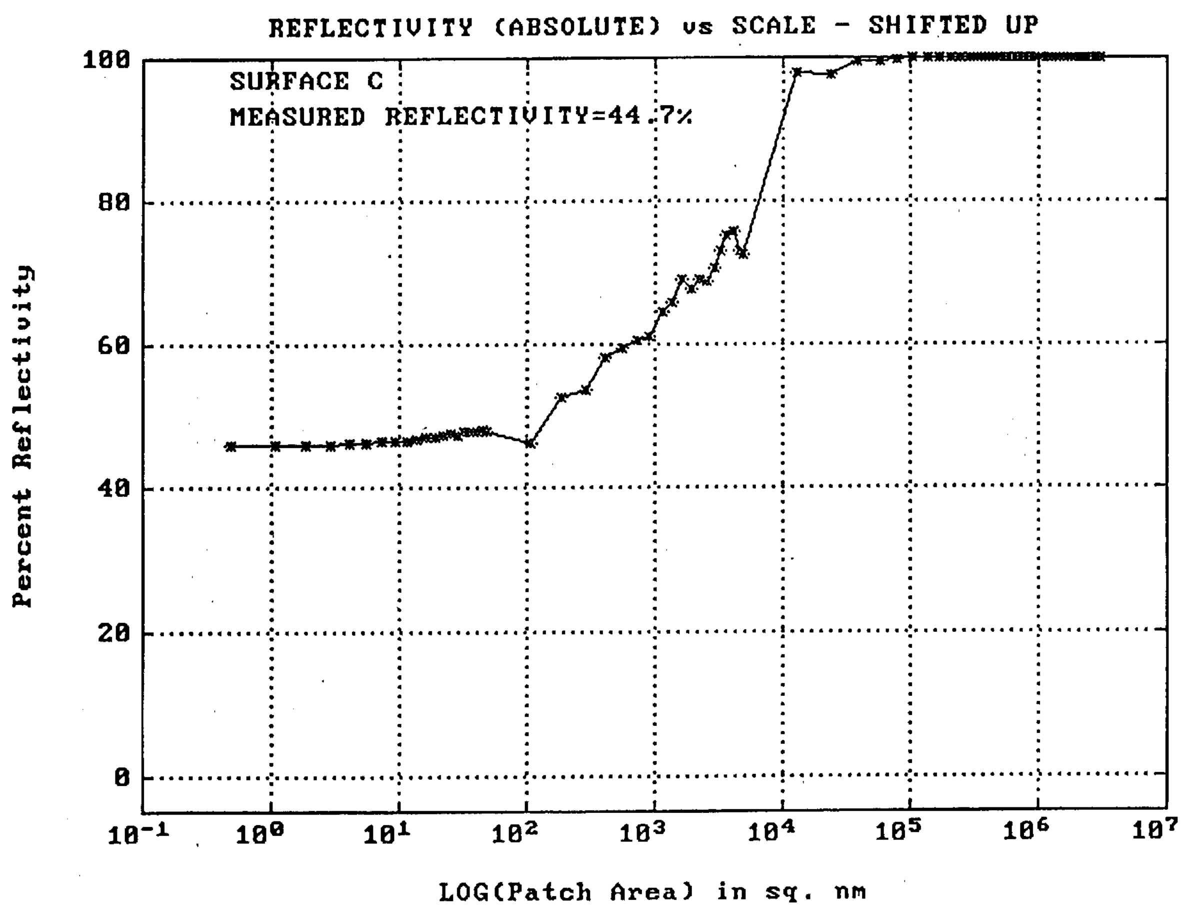
r^2=0.997406
y =-0.146713x+0.447666
4.338e+00 to 4.338e+01

Appendix B
Absolute Reflectivity vs. Patch Area

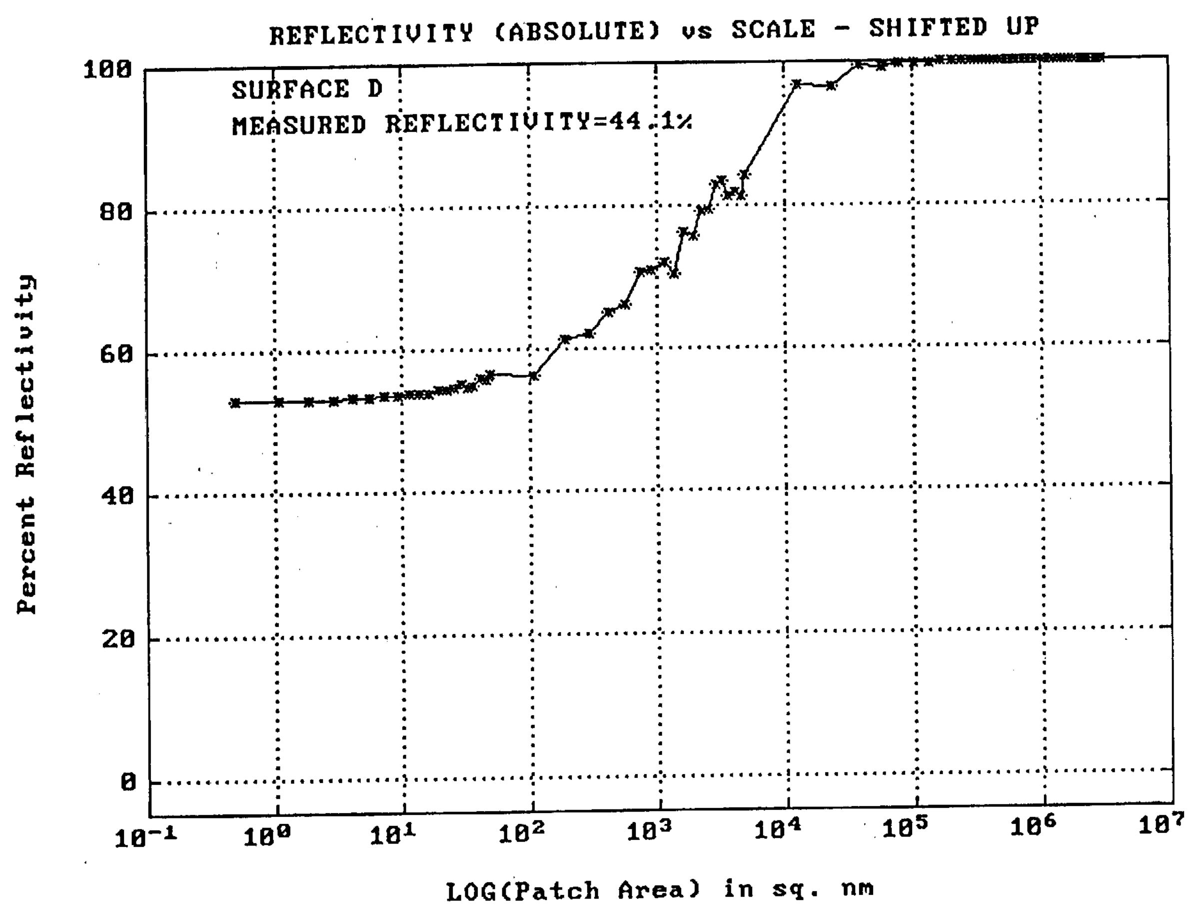

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE A
MEASURED REFLECTIVITY=69.1%
Percent Reflectivity
100
80
60
40
20
0
10-1
100
101
102
103
104
105
106
107
LOG(Patch Area) in sq. nm

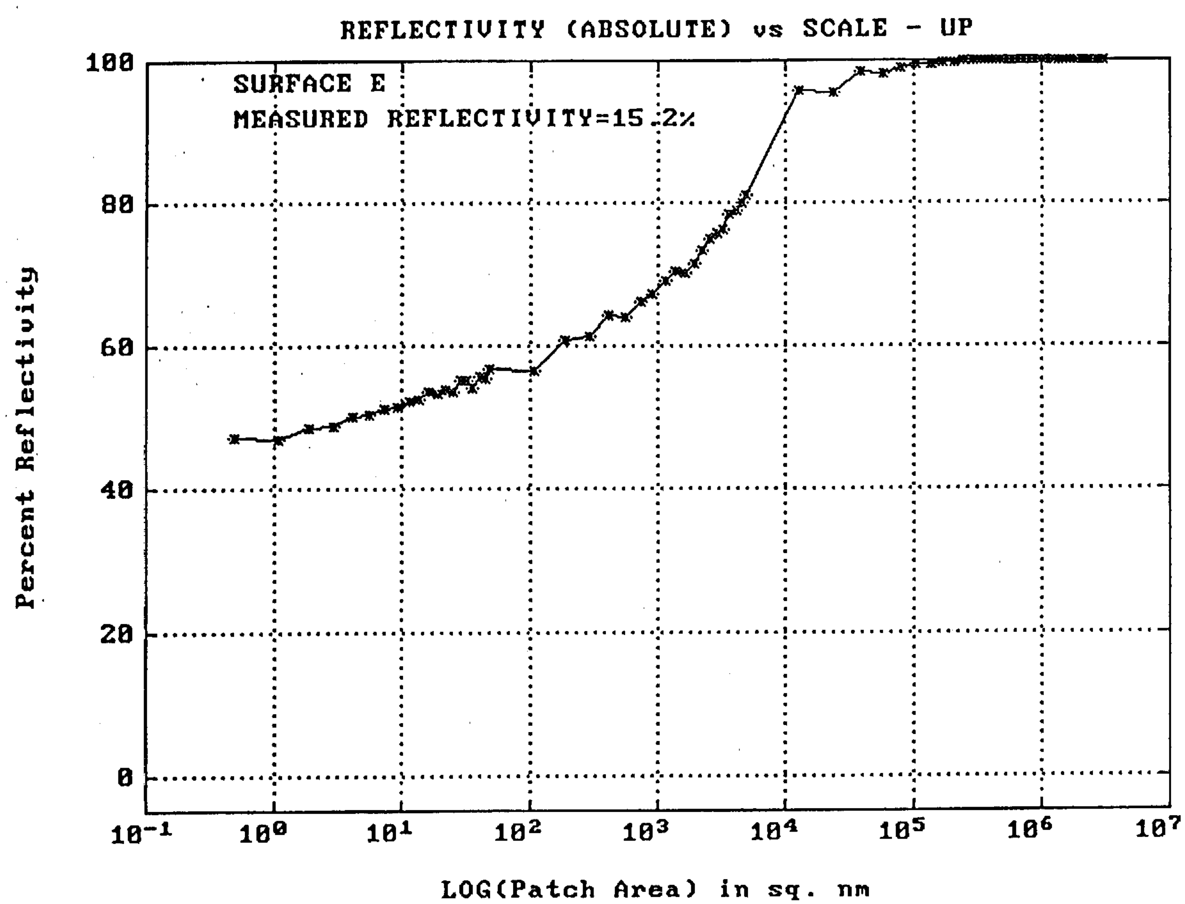


REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE B
MEASURED REFLECTIVITY=47.7%
100
80
60
40
20
0
Percent Reflectivity
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
LOG(Patch Area) in sq. nm

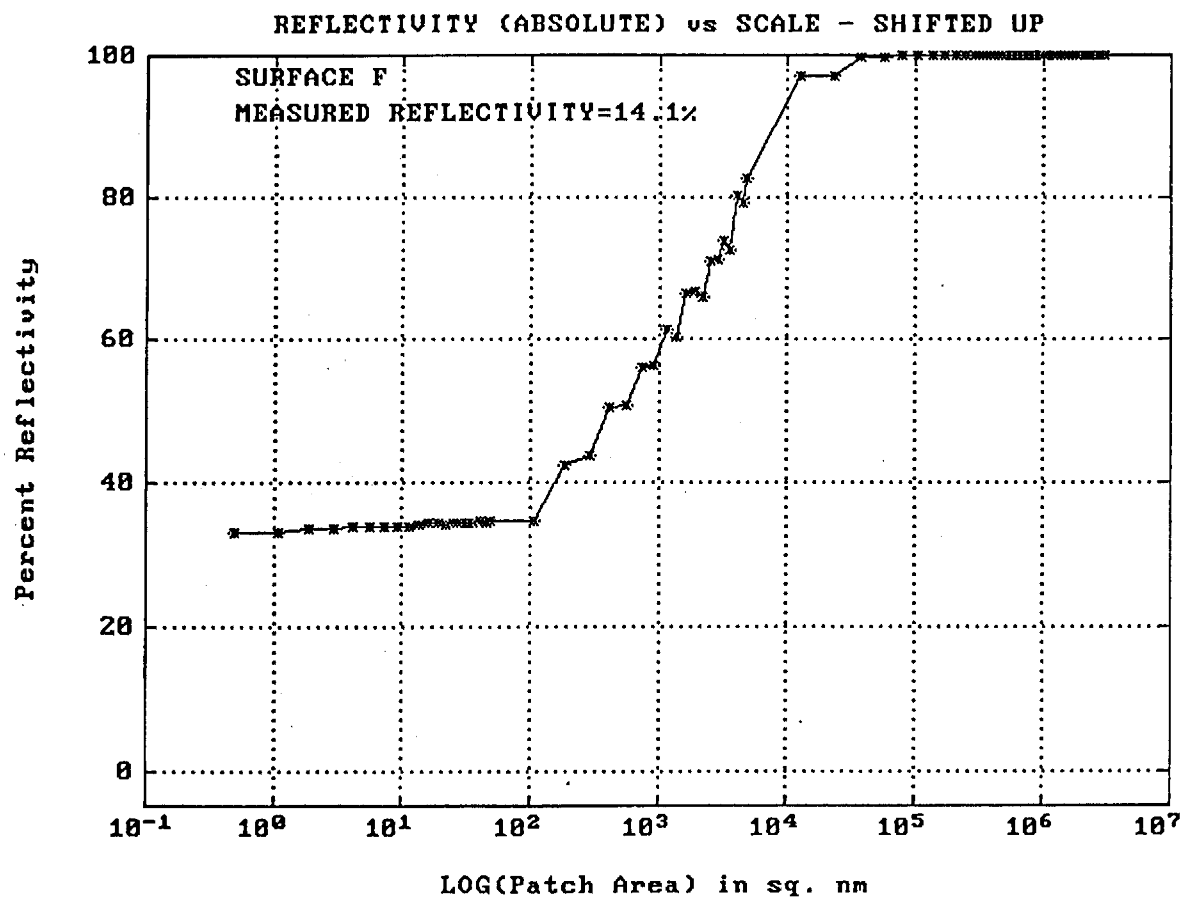


REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE C
MEASURED REFLECTIVITY=44.7%
Percent Reflectivity
100
80
60
40
20
0
10-1
100
101
102
103
104
105
106
107
LOG(Patch Area) in sq. nm

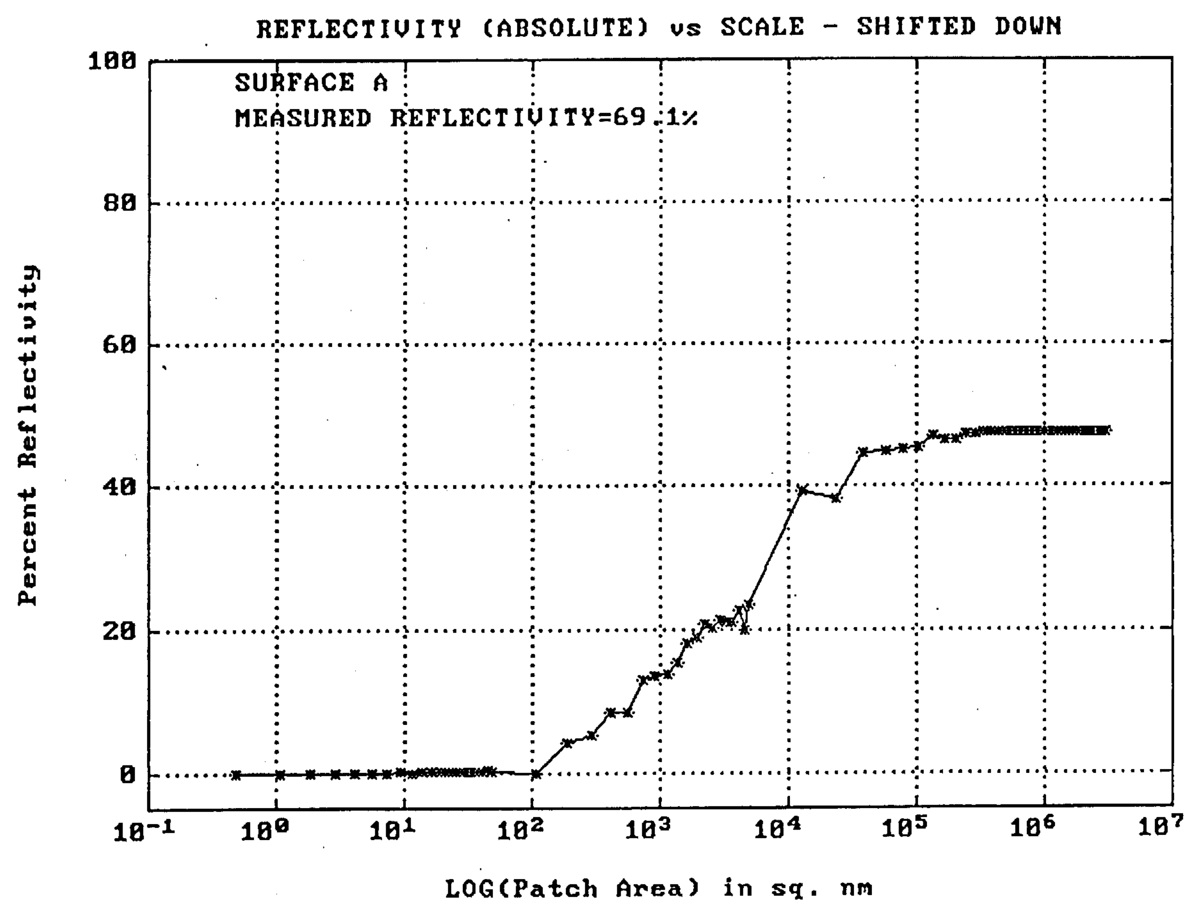

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE D
MEASURED REFLECTIVITY=44.1%
Percent Reflectivity
100
80
60
40
20
0
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
LOG(Patch Area) in sq. nm

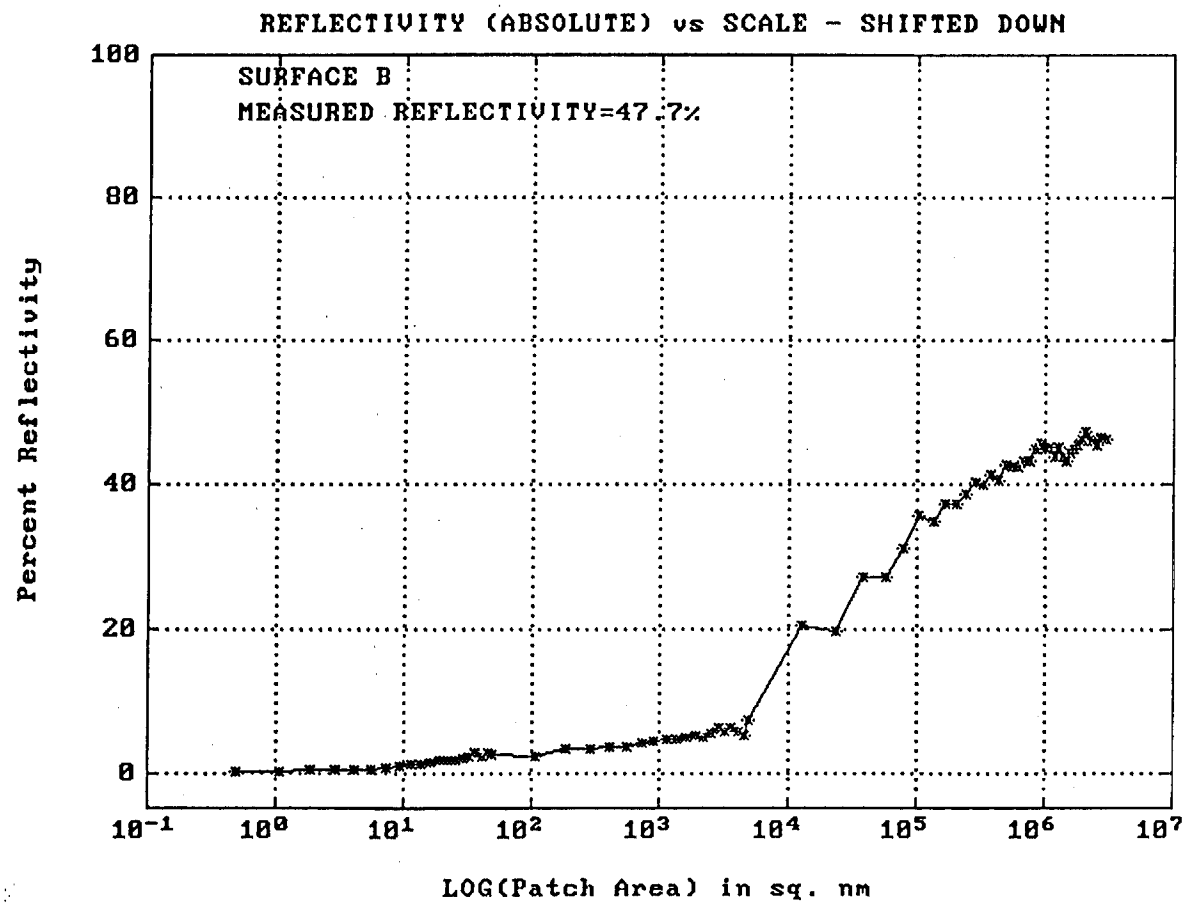


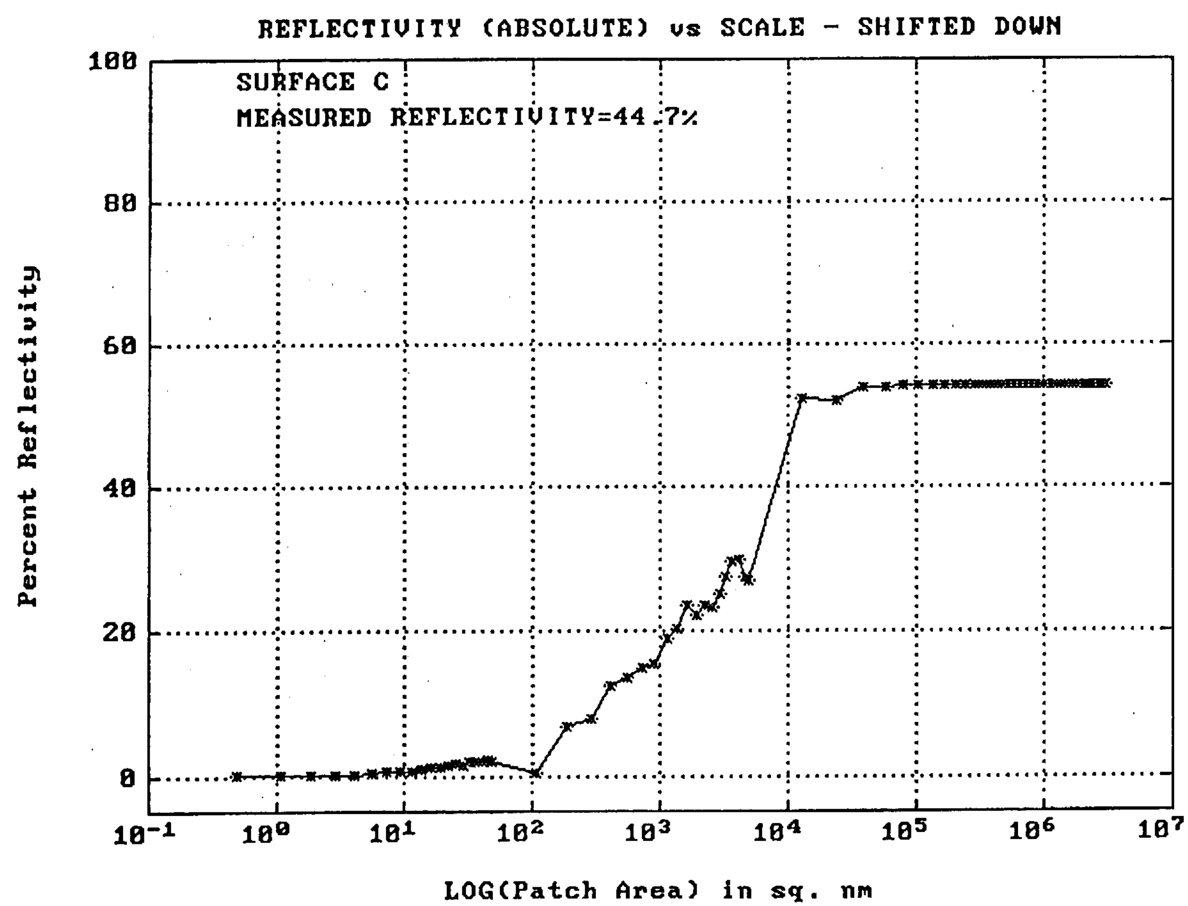
REFLECTIVITY (ABSOLUTE) vs SCALE - UP
SURFACE E
MEASURED REFLECTIVITY=15.2%
Percent Reflectivity
100
80
60
40
20
0
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
LOG(Patch Area) in sq. nm

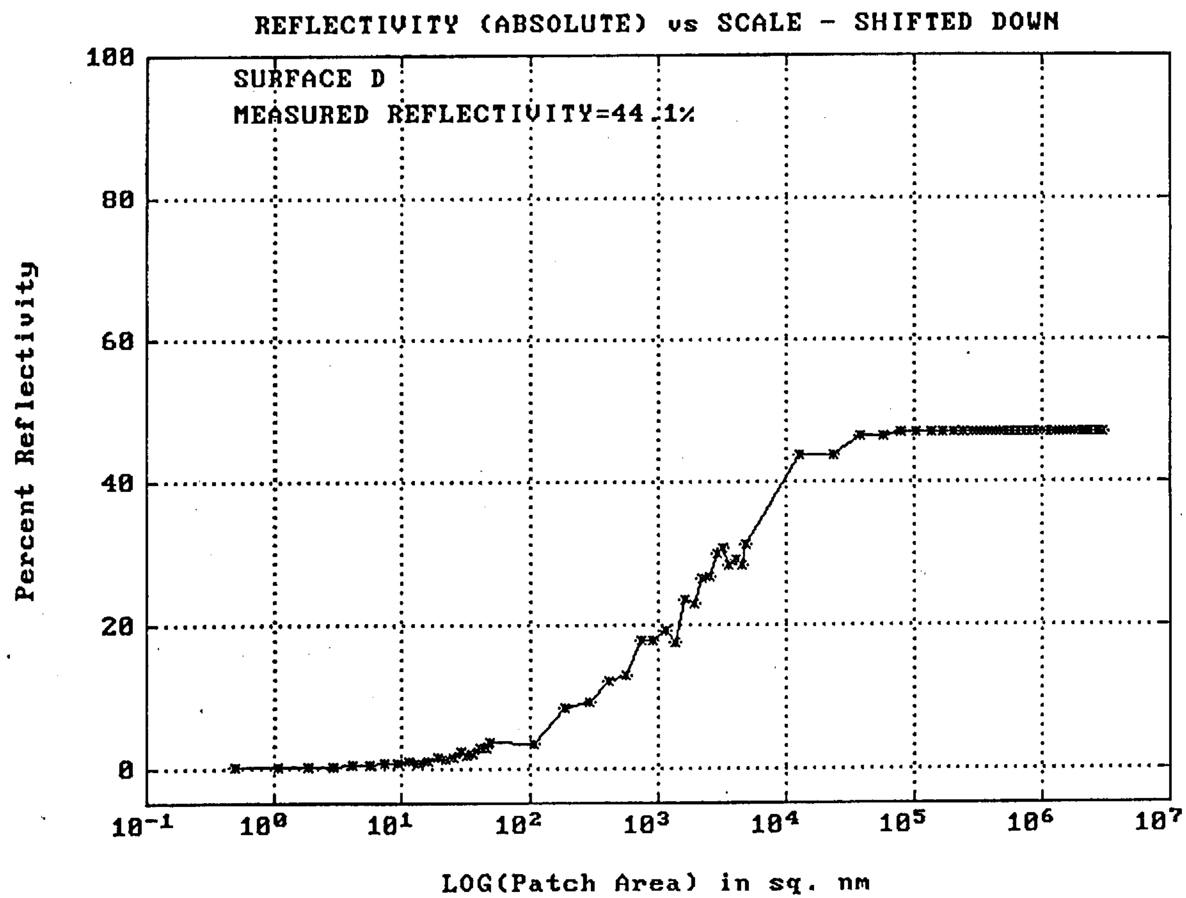


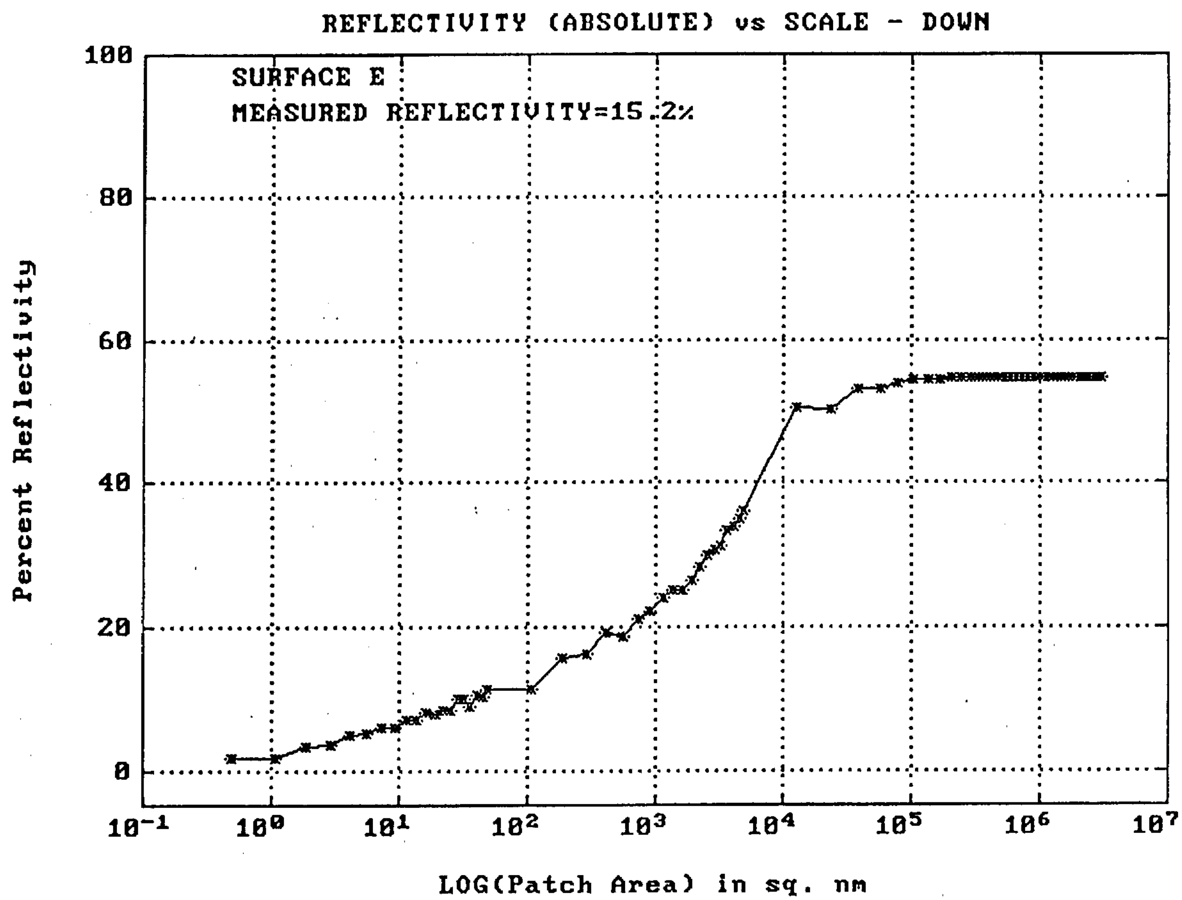
REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE F
MEASURED REFLECTIVITY=14.1%
Percent Reflectivity
100
80
60
40
20
0
10-1
100
101
102
103
104
105
106
107
LOG(Patch Area) in sq. nm


REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED DOWN
SURFACE A
MEASURED REFLECTIVITY=69.1%
Percent Reflectivity
100
80
60
40
20
0
10-1
100
101
102
103
104
105
106
107
LOG(Patch Area) in sq. nm

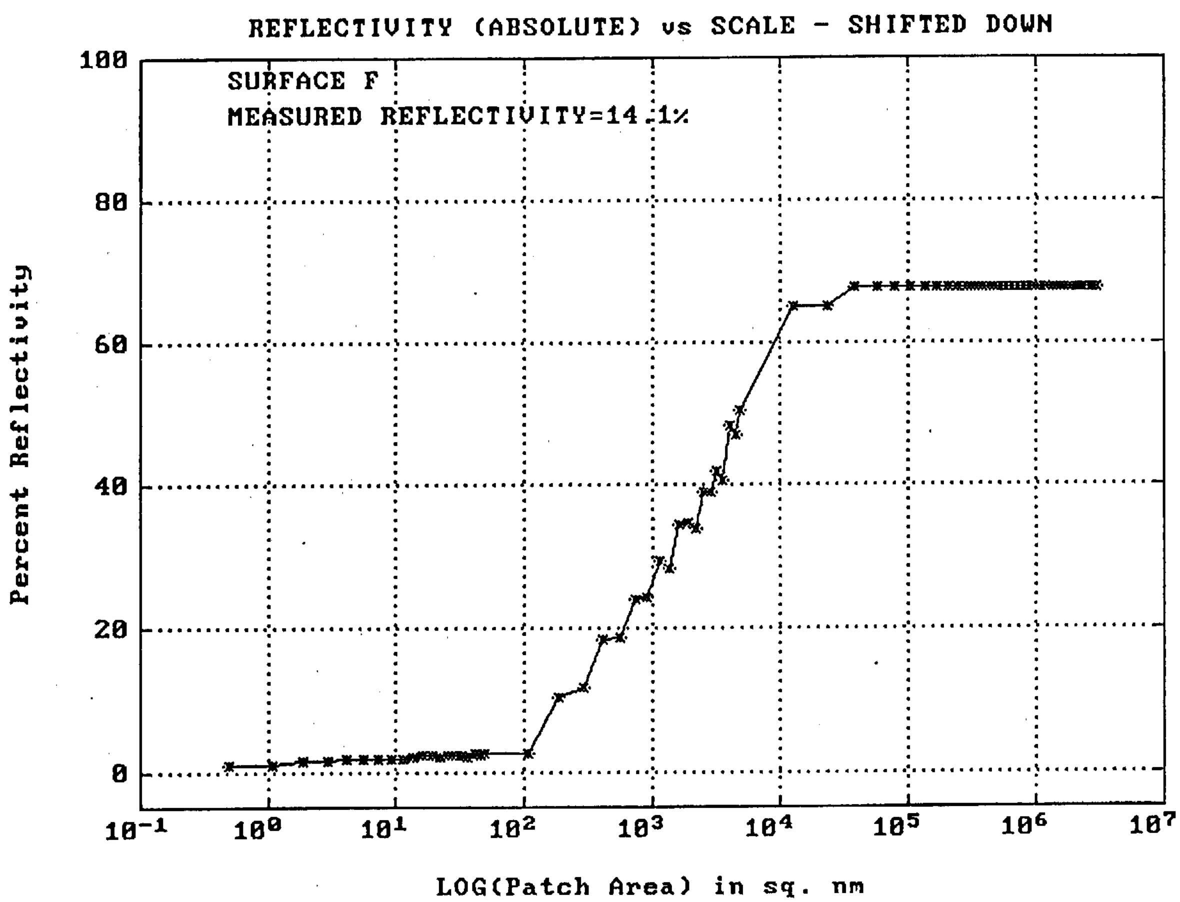

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED DOWN
SURFACE B
MEASURED REFLECTIVITY=47.7%
100
80
60
40
20
0
Percent Reflectivity
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
LOG(Patch Area) in sq. nm


REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED DOWN
SURFACE C
MEASURED REFLECTIVITY=44.7%
Percent Reflectivity
100
80
60
40
20
0
10-1
100
101
102
103
104
105
106
107
LOG(Patch Area) in sq. nm

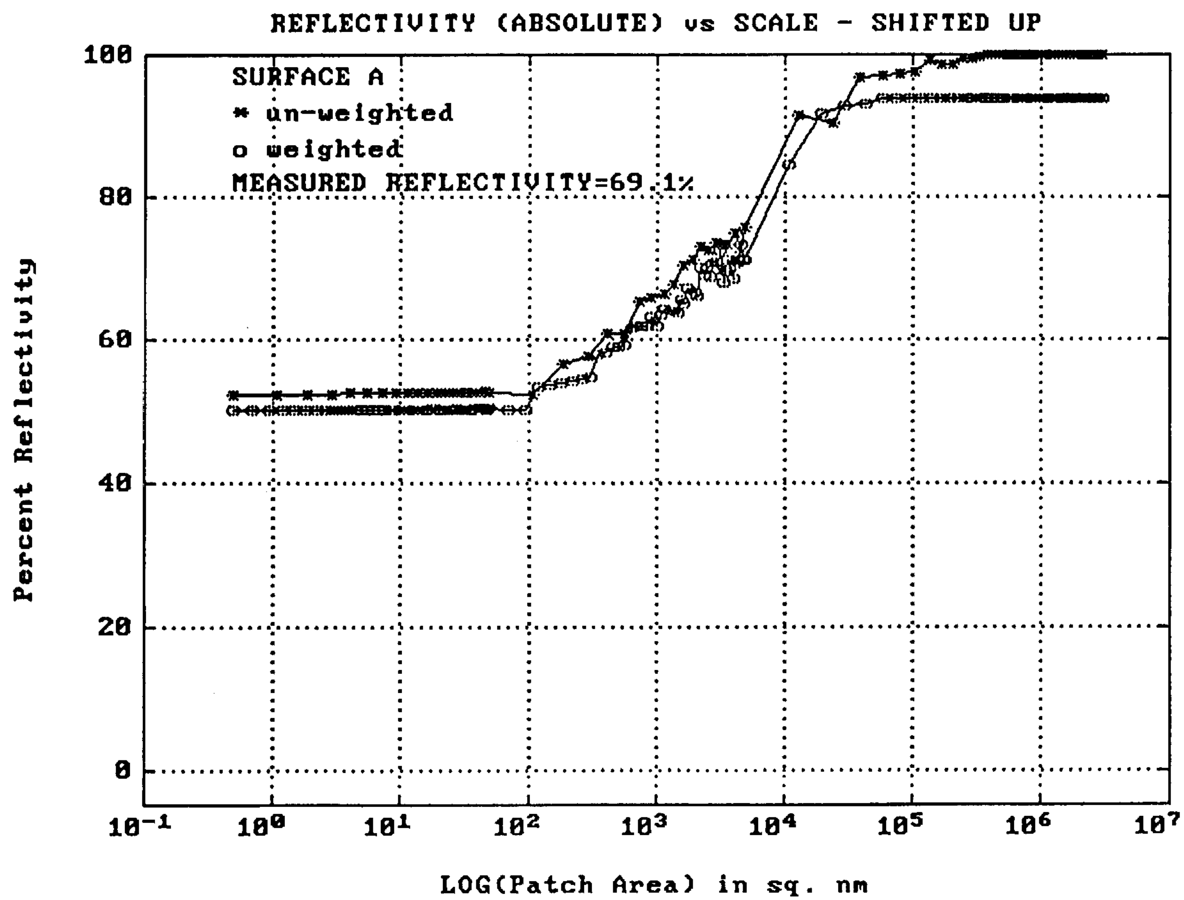

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED DOWN
SURFACE D
MEASURED REFLECTIVITY=44.1%
Percent Reflectivity
0
20
40
60
80
100
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
LOG(Patch Area) in sq. nm

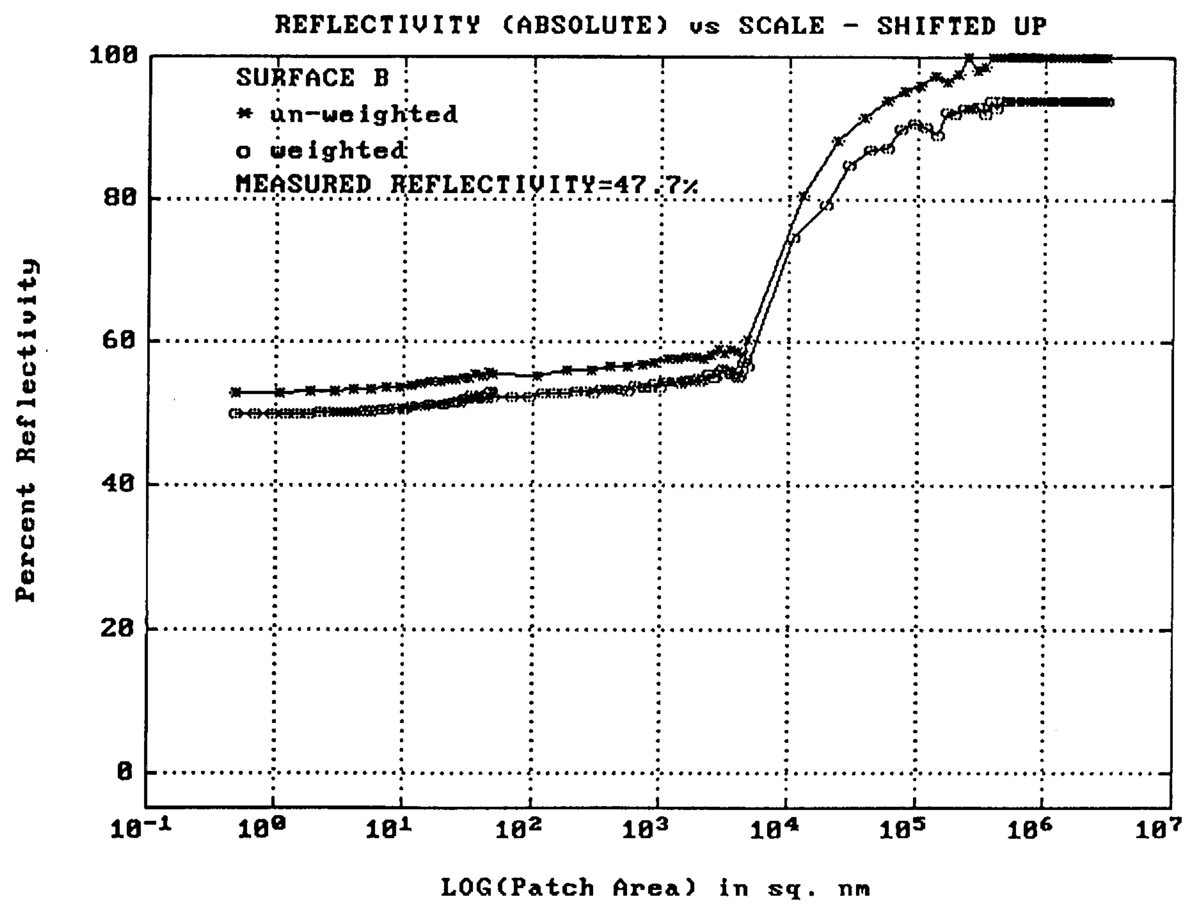


REFLECTIVITY (ABSOLUTE) vs SCALE - DOWN
SURFACE E
MEASURED REFLECTIVITY=15.2%
Percent Reflectivity
100
80
60
40
20
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
LOG(Patch Area) in sq. nm

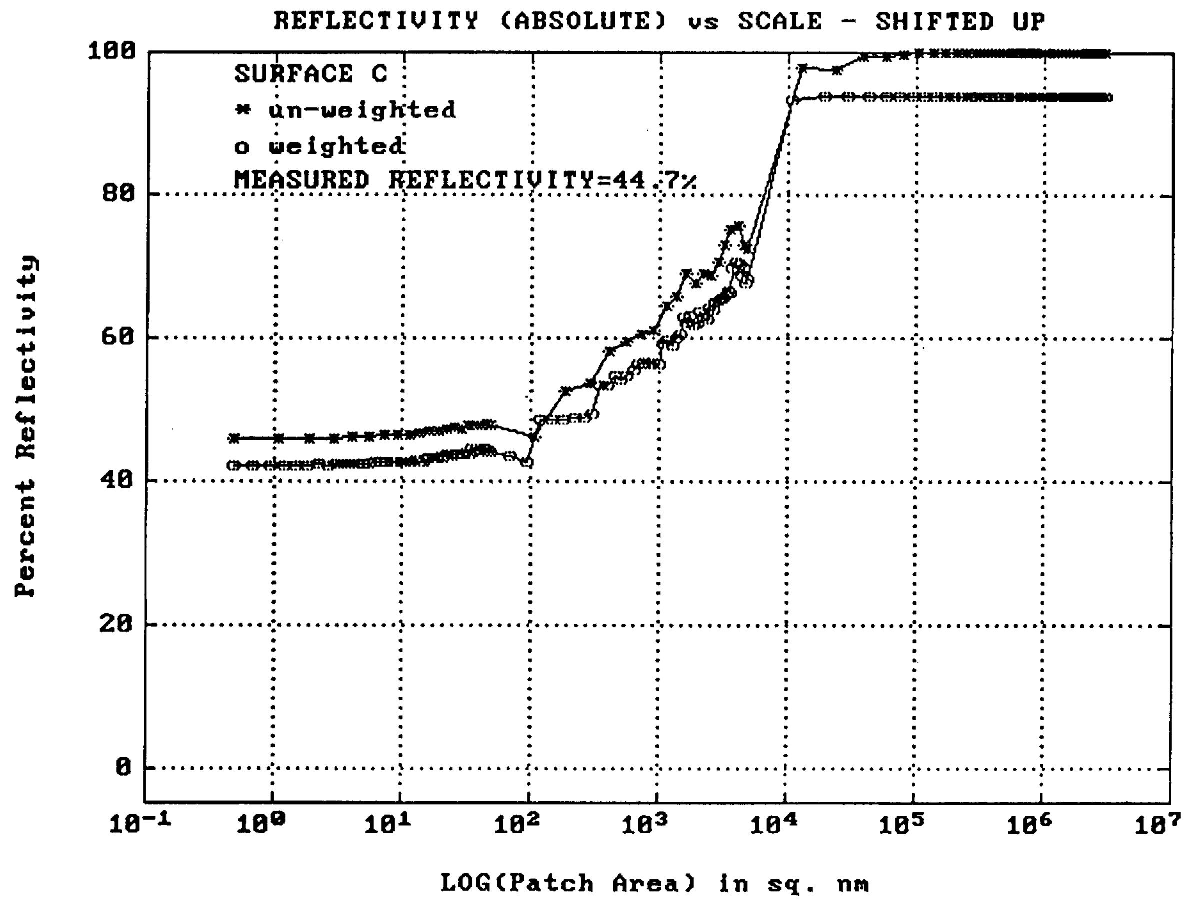

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED DOWN
SURFACE F
MEASURED REFLECTIVITY=14.1%
Percent Reflectivity
0
20
40
60
80
100
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
LOG(Patch Area) in sq. nm

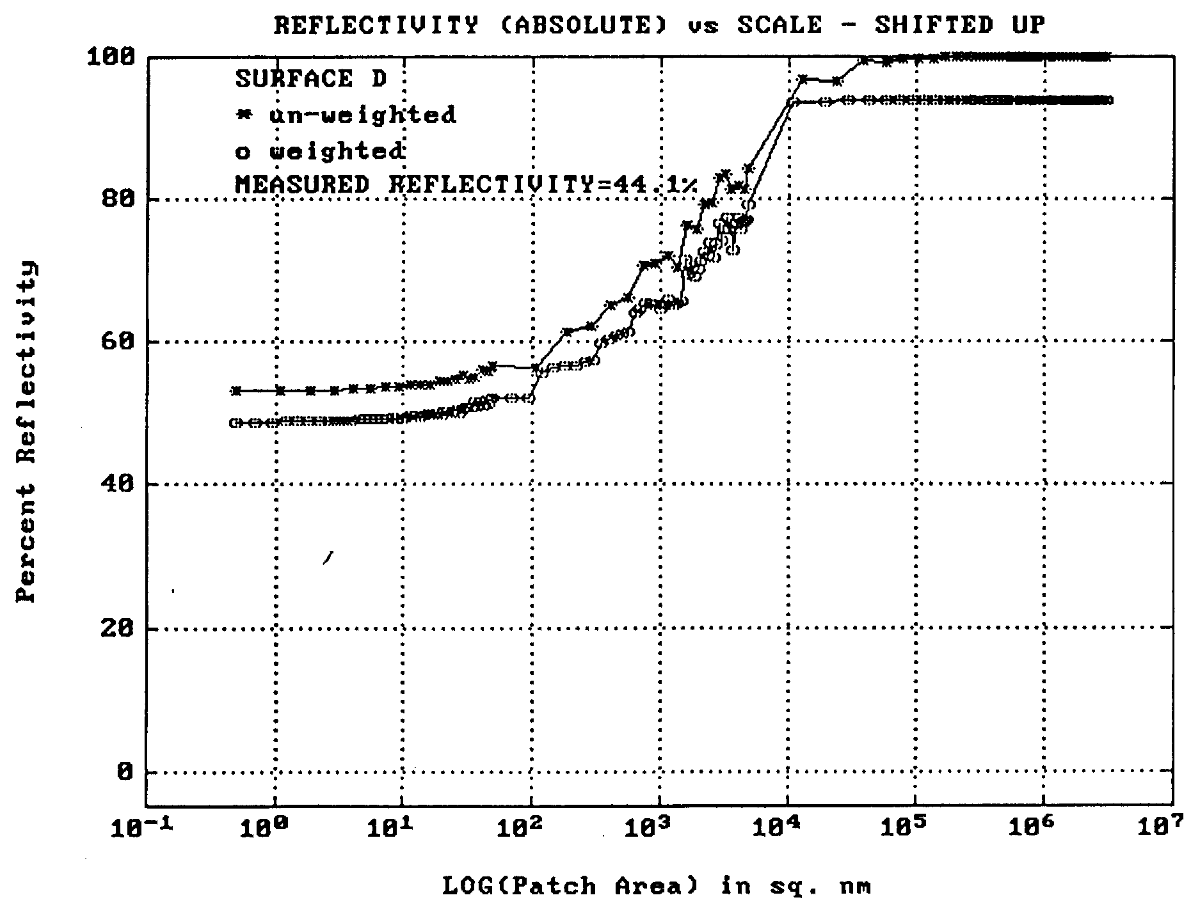
Appendix C
Cosine Weighted and Non-Weighted Absolute Reflectivity vs Patch Area

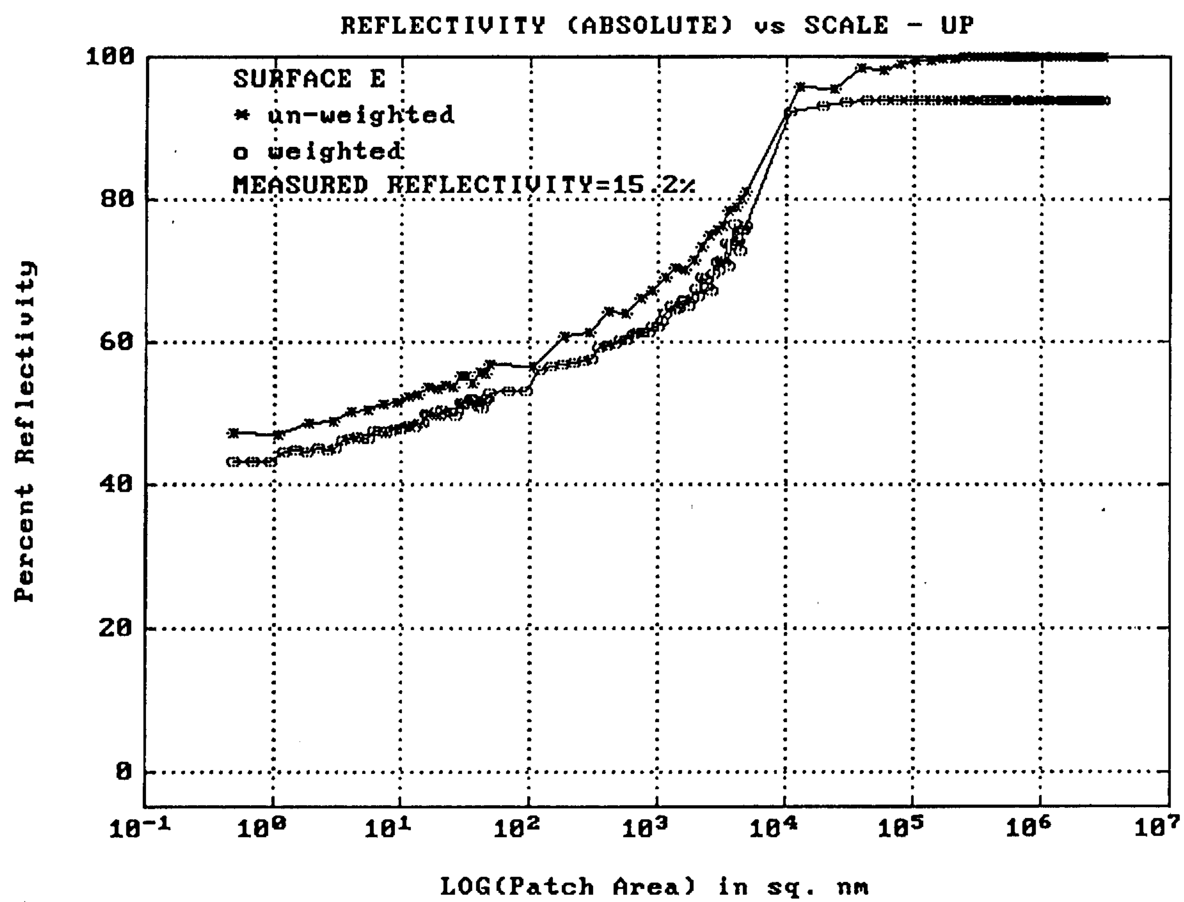

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE A
* un-weighted
o weighted
MEASURED REFLECTIVITY=69.1%
Percent Reflectivity
100
80
60
40
20
0
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
LOG(Patch Area) in sq. nm



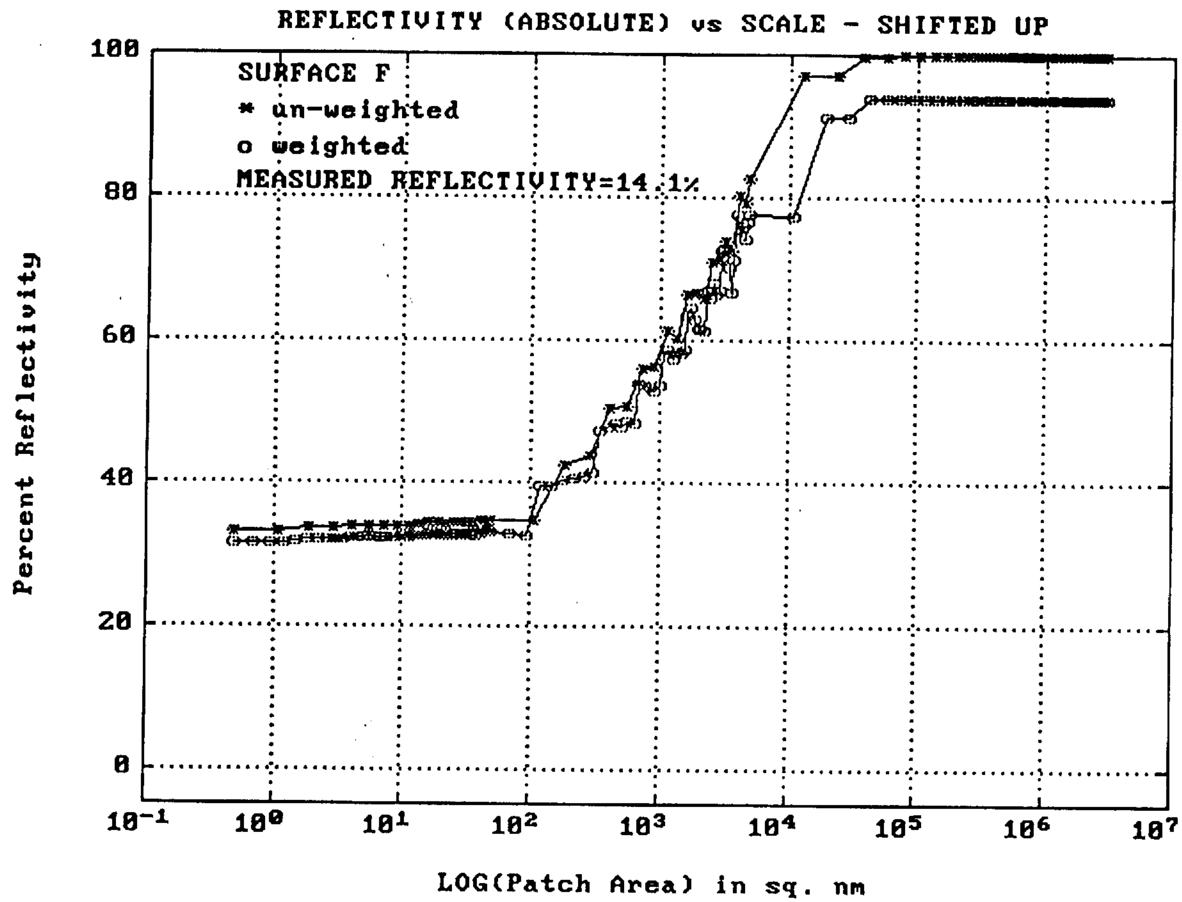
REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE B
* un-weighted
o weighted
MEASURED REFLECTIVITY=47.7%
Percent Reflectivity
100
80
60
40
20
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
LOG(Patch Area) in sq. nm


REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE C
* un-weighted
o weighted
MEASURED REFLECTIVITY=44.7%
Percent Reflectivity
100
80
60
40
20
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
LOG(Patch Area) in sq. nm

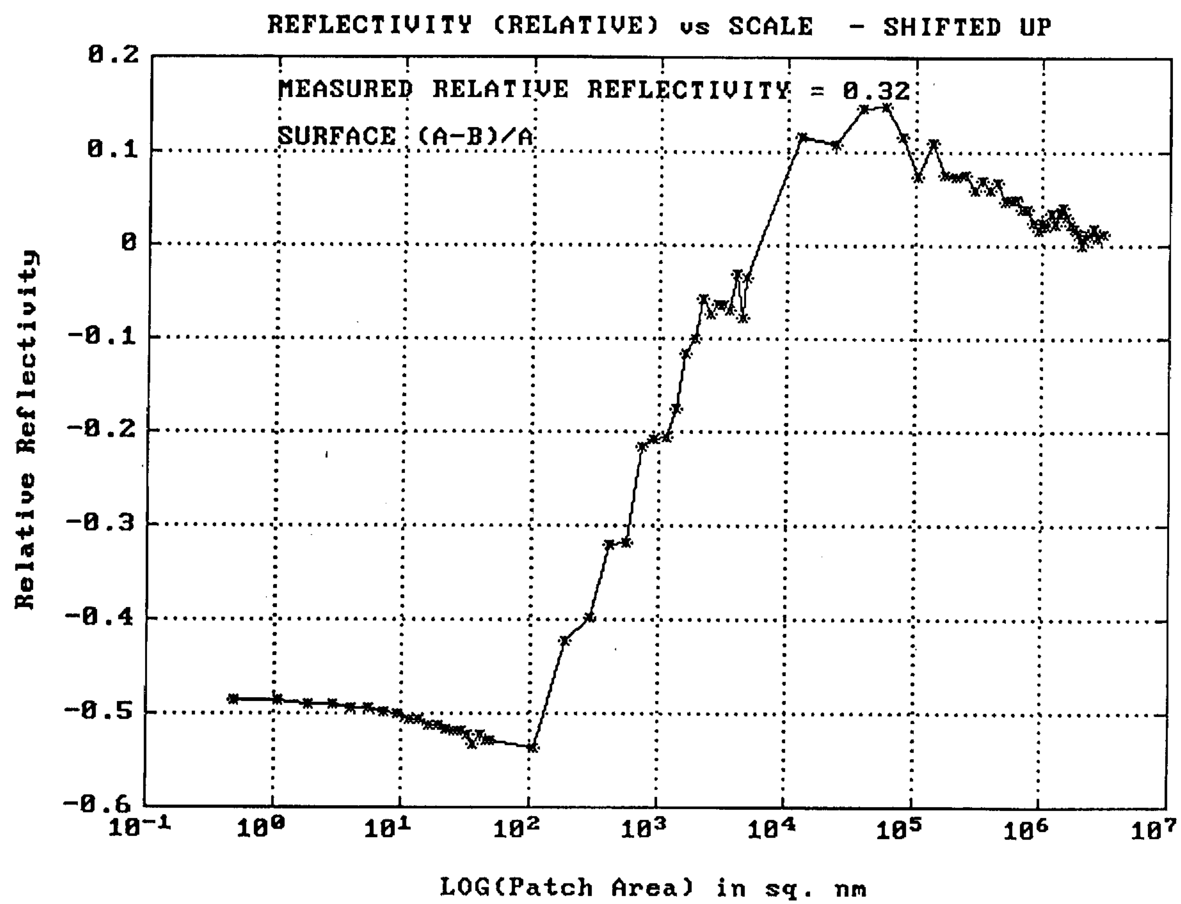

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE D
* un-weighted
o weighted
MEASURED REFLECTIVITY=44.1%
100
80
60
40
20
0
Percent Reflectivity
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
LOG(Patch Area) in sq. nm

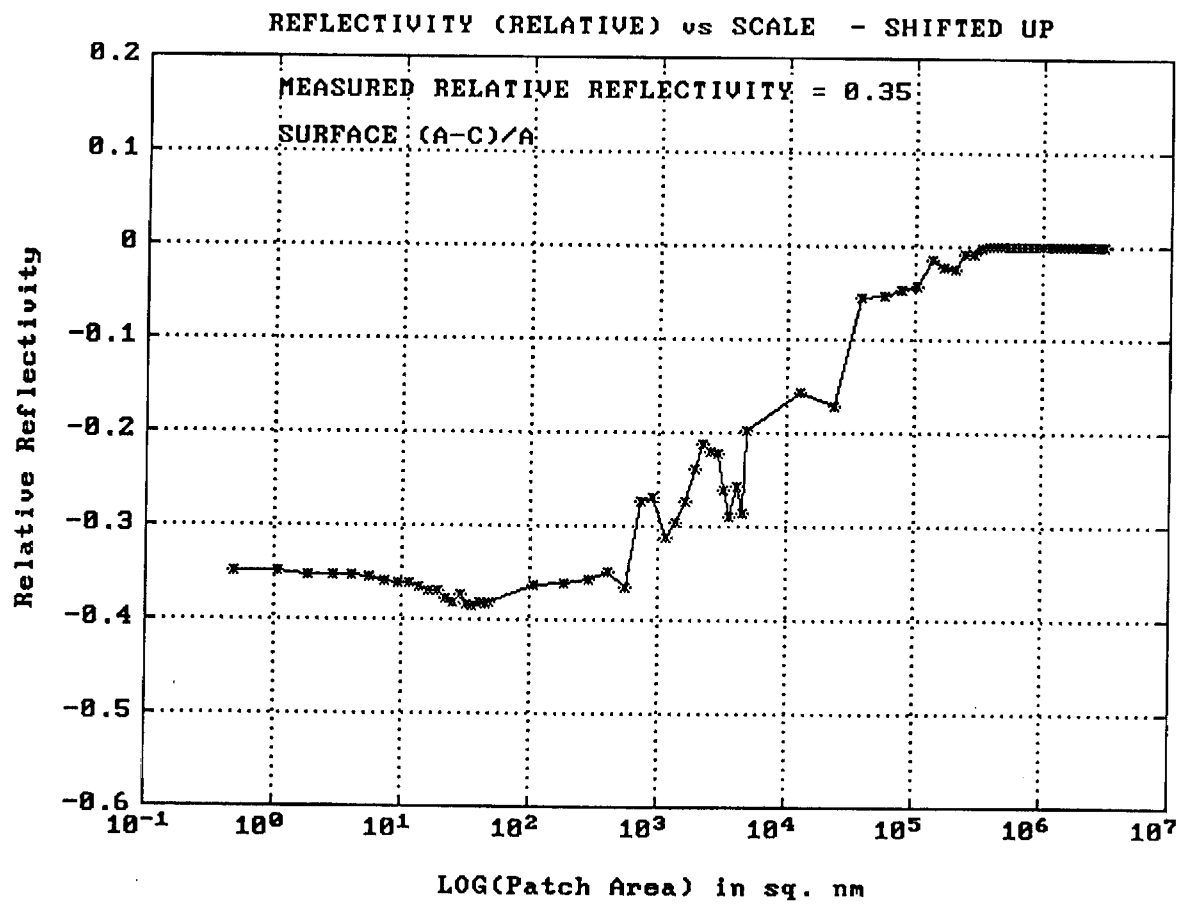


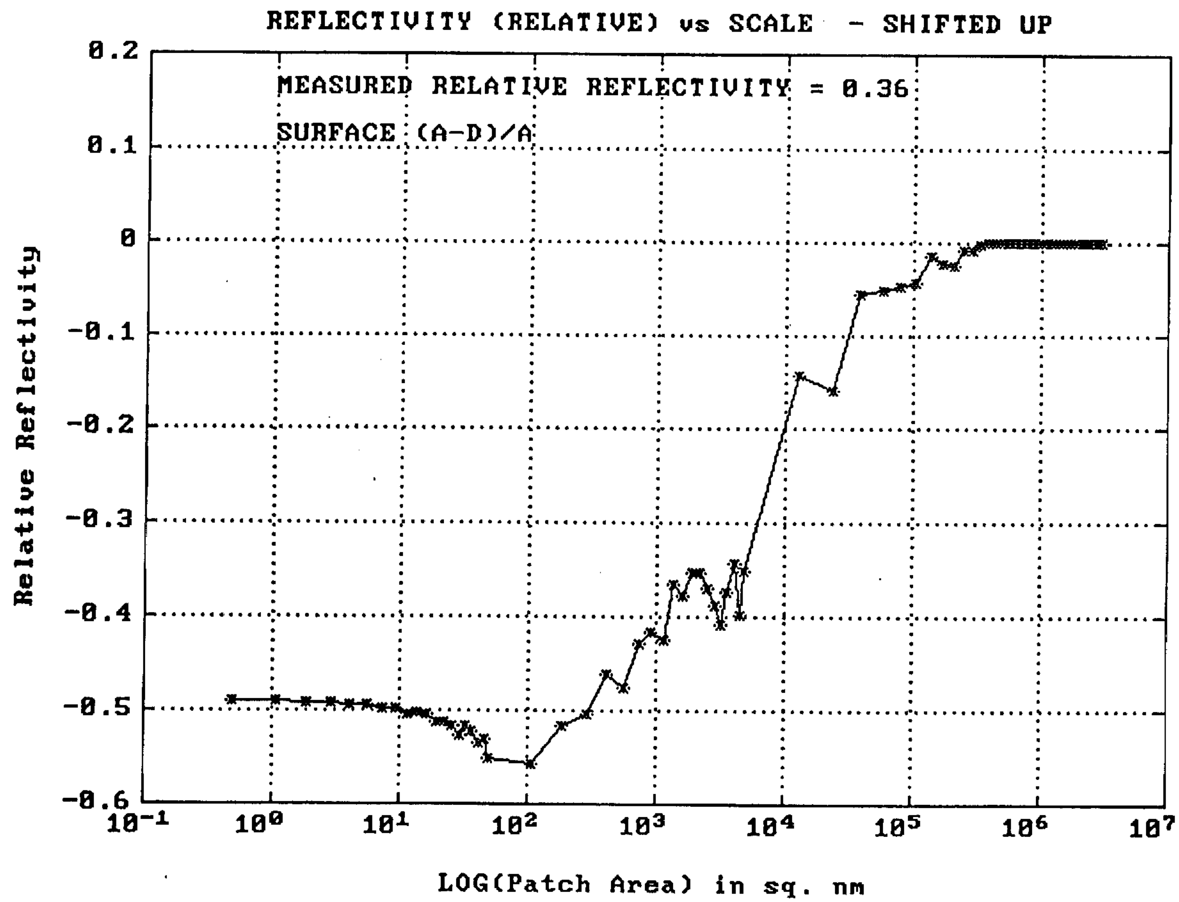
REFLECTIVITY (ABSOLUTE) vs SCALE - UP
SURFACE E
* un-weighted
o weighted
MEASURED REFLECTIVITY=15.2%
Percent Reflectivity
100
80
60
40
20
0
10-1
100
101
102
103
104
105
106
107
LOG(Patch Area) in sq. nm

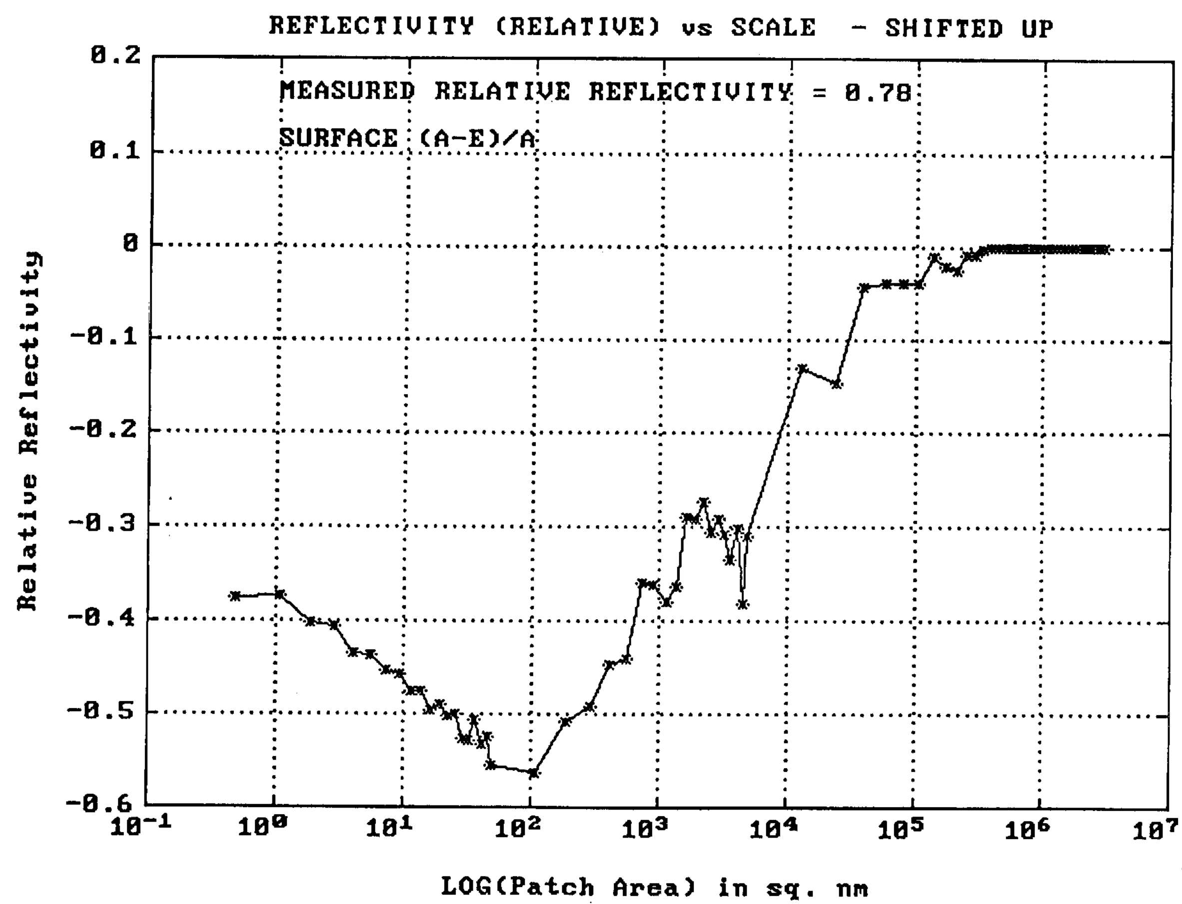

REFLECTIVITY (ABSOLUTE) vs SCALE - SHIFTED UP
SURFACE F
* un-weighted
o weighted
MEASURED REFLECTIVITY=14.1%
Percent Reflectivity
LOG(Patch Area) in sq. nm
100
80
60
40
20
0
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷

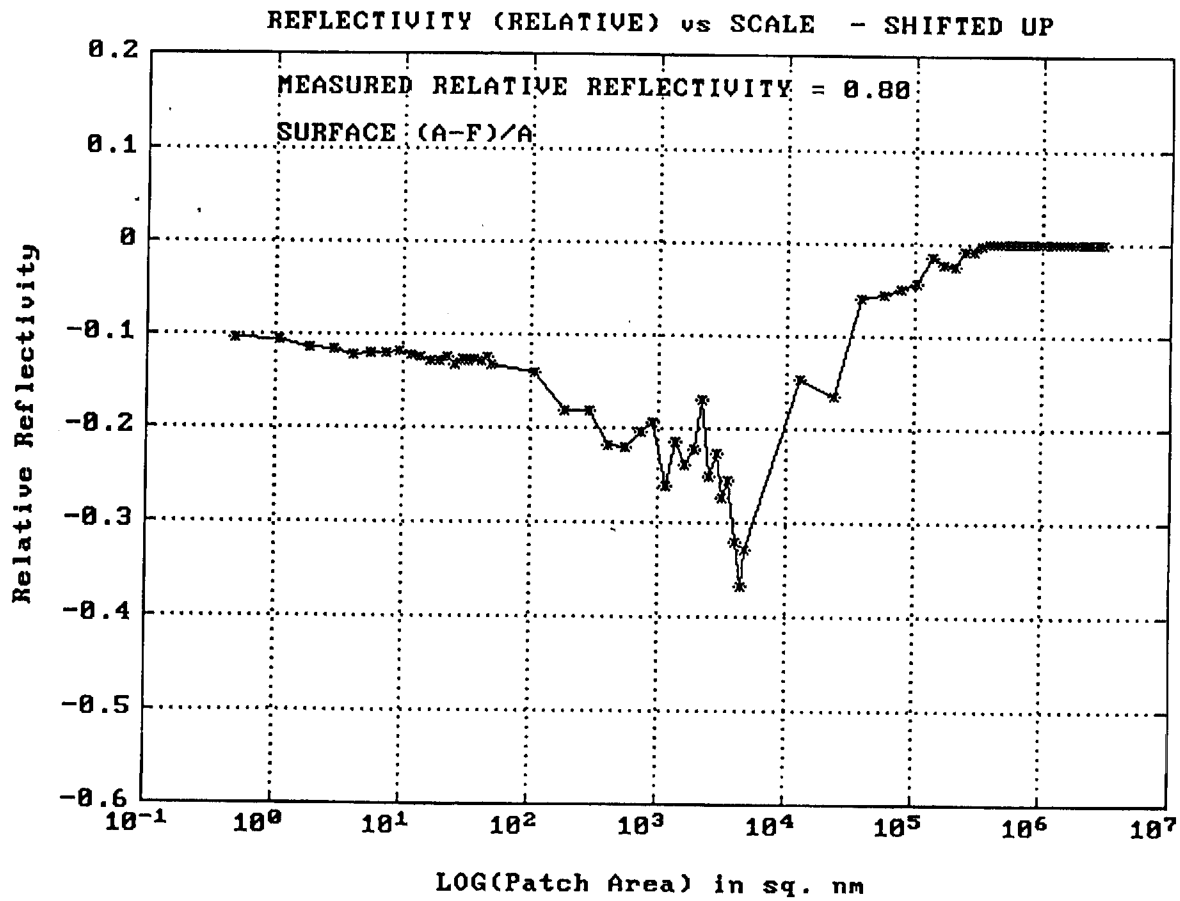
Appendix D
Relative Reflectivity vs. Patch Area


REFLECTIVITY (RELATIVE) vs SCALE - SHIFTED UP
MEASURED RELATIVE REFLECTIVITY = 0.32
SURFACE (A-B)/A
Relative Reflectivity
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
LOG(Patch Area) in sq. nm


REFLECTIVITY (RELATIVE) vs SCALE - SHIFTED UP
MEASURED RELATIVE REFLECTIVITY = 0.35
SURFACE (A-C)/A
Relative Reflectivity
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
LOG(Patch Area) in sq. nm


REFLECTIVITY (RELATIVE) vs SCALE - SHIFTED UP
MEASURED RELATIVE REFLECTIVITY = 0.36
SURFACE (A-D)/A
Relative Reflectivity
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
LOG(Patch Area) in sq. nm


REFLECTIVITY (RELATIVE) vs SCALE - SHIFTED UP
MEASURED RELATIVE REFLECTIVITY = 0.78
SURFACE (A-E)/A
Relative Reflectivity
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
LOG(Patch Area) in sq. nm


REFLECTIVITY (RELATIVE) vs SCALE - SHIFTED UP
MEASURED RELATIVE REFLECTIVITY = 0.80
SURFACE (A-F)/A
Relative Reflectivity
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
LOG(Patch Area) in sq. nm